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Intelligent System for Radial Distribution Load Flow

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***Abstract* — This paper shows an application of Artificial Neural Networks (ANNs) to determine the bus voltages and phase angles of a radial distribution system, without executing the complicated load flow algorithm, for any given load. The performance of the conventional load flow methods such as Newtoh-Raphson load flow, Fast decoupled load flow is found to be very poor under critical conditions such as high R/X ratio, heavily loading condition etc.To overcome the limitations of these regularly used methods a simple and reliable ladder iterative technique is used for solving the power balance equations of radial distribution system (RDS). The proposed method make use of a multi-layer feed forward ANN with error back propagation learning algorithm for calculation of bus voltages and its angles. A sample IEEE 33-bus is extensively tested with the proposed ANN based approach indicating its viability for RDS load flow assessment and results are presented.**

***Keywords*—Ladder Iterative Technique, R/X ratio, Artificial Neural Networks (ANNs), Backpropagation Network (BPN), Radial Distribution System (RDS), Forward-Backward Sweep.**

I. Introduction

The load-flow of distribution system is different from that of transmission system because of their high R/X ratio and radial topology. Convergence of load flow is utmost important[13]. Matrix based iterative methods do not lead themselves for radial distribution system owing to their poor performance under critical conditions and heavily loading conditions. A survey of literature shows that several methods for distribution system load flow have been proposed [1, 2, 3].However, all these methods fail to obtain a solution in many instances because of matrices. Large RDS have complicated structure and are subjected to changes in their topology frequently for load balancing, maintenance, emergency operations under the umbrella of Supervisory Control and Data Acquisition (SCADA), SCADA requires a fast and reliable distribution load flow algorithm that calculates the voltage solution very rapidly.

To overcome the limitations of these regularly used methods a simple and reliable ladder iterative technique is used for solving the power balance equations of radial distribution system (RDS) that is, ladder iterative technique is described for solving the radial system power balance equation treating every lateral and sub lateral line as an individual main line. Kirchoff's current law (KCL) and Kirchoff's voltage law (KVL) based forward and backward sweep algorithm is utilized for deriving magnitude of voltages and their phase angles[13].The computation of branch current depends only on the current injected at the neighboring node and the current in the adjacent branch. This approach starts from end nodes of sub lateral line, lateral line and main line and moves towards the root node during branch current evaluation. The node voltage calculation begins from the root node and moves towards the node situated at the far end of the main, lateral and sub lateral lines. [4].

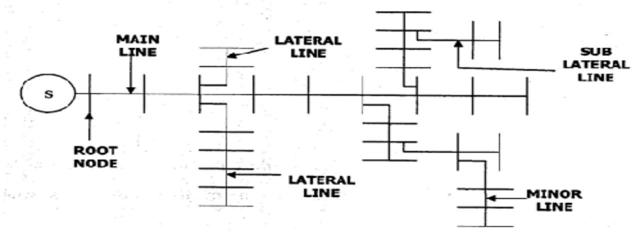

Fig.1. Single Line Diagram of a Radial Distribution Network

Main line: Line emanating from the root node.
Lateral line: Line emanating from the main line.
Sub lateral line: Line emanating from the lateral line.
Minor line: Line emanating from the sub lateral line.

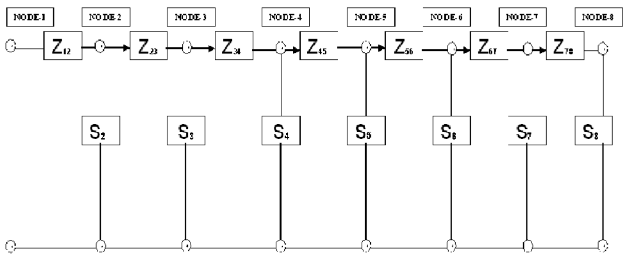

Fig.2. A Simple 8-Bus Ladder Network

Artificial Neural Networks (ANNs) approach for determine the bus voltages and phase angles of a radial distribution system, without executing the load flow algorithm, for any given load. Artificial Neural Networks (ANNs) are non-linear mapping structures based on the function of the human brains. They are powerful tools for modeling, especially when the underlying data relationship is unknown [12]. ANNs can identify and learn correlated patterns between input data sets and the corresponding target values. After training, it can be used to predict the output of new independent input data. ANNs can imitate the process of learning as human brain and can process complex and non-linear data even if data is imprecise and noisy. Therefore, here it is proposed to ideally suit the modelling of a balanced, complex and often non-linear radial distribution system as ANNs has the great capacity in predictive modelling and all the characters describing the unknown situation can be presented to the trained ANNs, and hence the prediction of RDS without any mathematical iterative and computational method is guaranteed.

In this paper, firstly an uncomplicated ladder iterative technique is described for solving the radial system power balance equation. The aim of using this technique is to reduce the data preparation and to assure computation for any type of numbering scheme for node and branch. A data base providing information of the possible real and reactive power demands at different buses and their corresponding voltage magnitude and phase angles is created. Secondly, ANN-Back Propagation Network is introduced with brief introduction of its architecture, training algorithm and recognition phase. Thirdly, an implementation of BPN for determining bus voltages and the corresponding angles is been shown, followed by the results of a sample IEEE test system studied by the proposed method. Finally, the conclusion is presented.

II. Ladder Network Technique

It is assumed that the ladder network parameters for lines, loads and substation voltage VS are known. If the line impedances, rated voltage and the complex power at each node are known then the values of the current, voltage, active and reactive power can be calculated using these called ladder iterative technique [12]. Iteration of the ladder iterative technique exists of two steps: forward sweep and backward sweep. Considering an IEEE-33 bus radial distribution grid fig.5. Calculations can be done as follows:

A. Forward sweep:

- Assume rated voltage V_S at the end node voltage ($V_{(18)}$,$V_{(22)}$,$V_{(25)}$,$V_{(33)}$) is 12660+j0 (for first iteration only) and equals the value Calculated in the backward sweep in the subsequent iteration.
- Starting with the end node 33 and calculate the node current $I_i = (S_i/V_i)^*$. Apply the Kirchhoff's current law to determine the current flowing from node 32 towards node 33: $I_{(32,33)} = I_{(33)} = (S_{(33)}/V_{(33)})^*$.
- Calculate with this current the voltage:
  $V_{(32)} = V(33) + Z(32,33)I(32,33)$
- *Calculate* with this voltage the current, $I_{(32)} = (S_{(32)}/V_{(32)})^*$. Apply the Kirchhoff's current law to determine the current flowing from node 31 toward node 32: $I_{(31,32)} = I_{(32,33)} + I_{(33)}$.
- Using the current $I_{(31,32)}$ Calculate the voltage:
  $V_{(31)} = V_{(32)} + Z_{(31,32)} I_{(31,32)}$
- Similarly Calculate till the junction node.
- Calculate with this current the voltage: $V_{(26)} = V_{(27)} + Z_{(26,27)} I_{(26,27)}$
- Calculate with this voltage the current $I_{(26)} = (S_{(26)}/V_{(26)})^*$. Apply the Kirchhoff's current law to determine the current flowing from node 6 toward node 26: $I_{(6,26)} = I_{(26,27)} + I_{(26)}$.
- Calculate with this current the voltage:
  $V_{(6)} = V_{(26)}+ Z_{(6,26)} I_{(6,26)}$. Node 6 is a junction node.
- Select node 18 and Calculate the node current, $I_{(18)} = (S_{(18)}/V_{(18)})^*$. Apply the Kirchhoff's current law to determine the current flowing from node 17 toward node 18: $I_{(17,18)} = I_{(18)}$.
- Calculate with this current the voltage:
  $V_{(17)} = V_{(18)}+ Z_{(17,18)} I_{(17,18)}$.
- Calculate with this voltage the current, $I_{(17)} = (S_{(17)}/V_{(17)})^*$,Apply the Kirchhoff's current law to determine the current flowing from node 16 toward node 17: $I_{(16,17)} = I_{(17,18)} + I_{(17)}$.
- Using the current $I_{(16,17)}$ Calculate the voltage:
  $V_{(16)} = V_{(17)}+ Z_{(16,17)} I_{(16,17)}$.
- Similarly Calculate till the junction node.
- Calculate with this current the voltage:
  $V_{(7)} = V_{(8)} + Z_{(7,8)} I_{(7,8)}$.
- Calculate with this voltage the current, $I_{(7)} = (S_{(7)}/V_{(7)})^*$. Apply the Kirchhoff's current law to determine the current flowing from node 6 toward node 7: $I_{(6,7)} = I_{(7,8)}+I_{(7)}$.
- Calculate with this current the voltage:
  $V'_{(6)} = V_{(26)} + Z_{(6,26)}I_{(6,26)}$. This will be referred to as "the most recent voltage at node 6".
- Calculate with the most recent voltage ($V'_{(6)}$) at node 6 the current $I_{(6)} = (S_{(6)}/V_{(6)})^*$. Apply the Kirchhoff's current law to determine the current:
  $I_{(5,6)} = I_{(6,7)} + I_{(6,26)} + I_{(6)}$.
- Similarly Calculate till the junction node.
- Using the current $I_{(1,2)}$ Calculate the voltage:
  $V_{(1)} = V_{(2)}+ Z_{(1,2)} I_{(1,2)}$.

At the end of the forward sweep compare the calculated magnitude of the rated voltage at node 1 to the specified source voltage.

$$\text{Voltage Difference (VD)} = ||V_s|-|V_1||$$

Stop if the VD is less than a specified tolerance i.e., if VD < 0.001 pu (≈12V) else the backward sweep begins. The backward sweep begins at the node 1 with the rated voltage $V_S = V_1 = 12660 + j0$ Volts.

B. Backward sweep:

- Start with node 1 and $V_{(1)} = V_{(S)}$.
- Calculate the voltage $V_{(2)} = V_{(1)} - Z_{(1,2)}I_{(1,2)}$.
- Calculate the voltage $V_{(3)} = V_{(2)} - Z_{(2,3)}I_{(2,3)}$.
- Calculate the voltage $V_{(4)}$ to $V_{(32)}$ similarly.
- Calculate the voltage $V_{(33)} = V_{(32)} - Z_{(32,33)}I_{(32,33)}$.

After the backward sweep the first iteration is completed. At this point the forward sweep will be repeated, only this time starting with the new voltage at end nodes. These steps will be repeated until the error is less than the specified tolerance. At the substation the voltage is mostly taken 5% bigger than the rated voltage.

The key to understanding the forward and backward sweep method is that

- The forward sweep is simply obtaining estimates of currents in each of the segments. In the forward sweep, voltage accuracy is not important.
- The backward sweep is concerned with accuracy of resulting voltages.

So the method is the same as previously given with the following additional rules:

1. Begin the algorithm by assuming nominal voltages at all far-end load nodes.
2. Compute all downstream currents (those currents flowing from a junction node towards the load) before moving upstream from the junction node.
3. Assign to the junction node a voltage computed based on the forward sweep done on the last downstream branch emanating from that junction node. (Note here that this is arbitrary – we could take the voltage

computed based on the forward sweep from any of the downstream branches emanating from the junction node).

4. Use forward sweep currents in all backward sweep calculations.

III. ANN-BPN ARCHITECTURE

The most widely used learning algorithm in an ANN, the Backpropagation algorithm is presented in this context. The neural network structure defines its structure including number of hidden layers, number of hidden nodes and number of output nodes (Fig-3). Fig-4 shows the architecture of BPN to have three layers, namely-input, hidden and the output layers. The Multilayered Perceptron (MLP) network is trained using one of the supervised learning algorithms of which the best. It uses the data to adjust the network's weights and thresholds so as to minimize the error in its predictions on the training set. Many different sets of the input and their corresponding output vectors are considered during the training. To determine the weights between the input, hidden and output layers, the training phase is used.

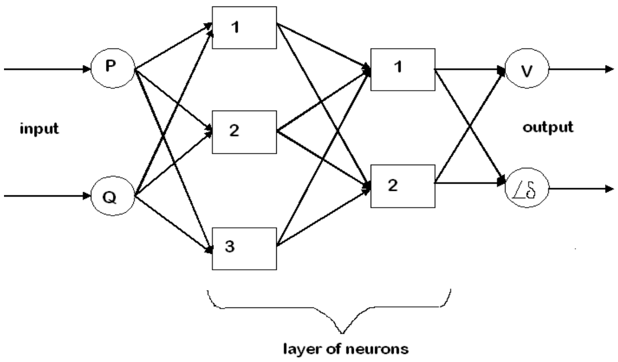

Fig.3. Neural Network

Typically in this study neurons used are the sigmoid activation function defined by the below equation:

$$[Neuron\ Input] = \frac{1.0}{1.0 + e^{-\alpha v}} \quad (1)$$

Here, α is the abruptness of the sigmoid activation function and v is the total input to the neuron. Let the vector X represent an input layer as in Fig.4.The net input at the hidden layers is computed by the matrix equation below:

$$V_H = [WH]\ X \quad (2)$$

Where WHji denotes the weight between i^{th} input layer node and j^{th} hidden layer node. The output of the hidden layer node is given by,

$$Y_H = \phi\ (V_H) \quad (3)$$

Here ϕ is the appropriate activation function. In a similar manner the total input at the output layer is given by the following equation:

$$V_o = [WO]V_H \quad (4)$$

The output of the output layer node is given by,

$$Y = \phi\ (V_O) \quad (5)$$

The steps of the well established training algorithm based upon Network's steepest descent technique is as given below:

1. Read the training set and randomly initialize the weights. Set iteration index n=1.
2. Set training set index p=1.
3. Propagate X^P through the network.
4. Determine the error vector of the p^{th} training set, $E^p = O^p - Y^p$
   Where O^p is the vector of expected output.
5. Correct the weights using Newton's steepest descent technique.
6. If p < number training sets P, set $p = p + 1$ and go to step-3.
7. If $\sum_{p=1}^{p} |E^p|^2 >$ tolerance ϵ, increment the iteration index n and go to step-2.

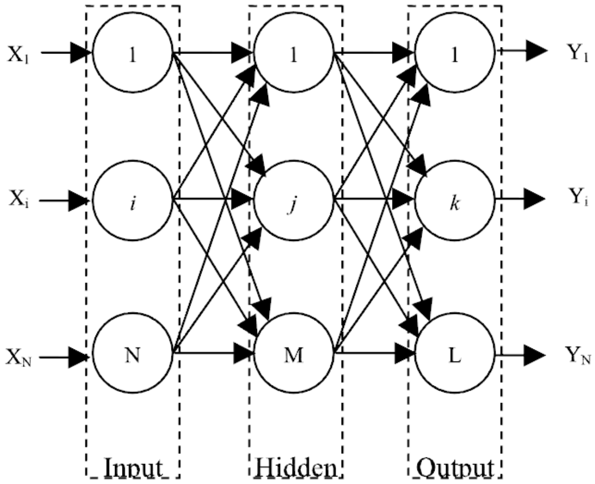

Fig.4. Basic BPN Architecture

The above method explained is tested successfully and requires the input and output to be from a continuous domain. Moreover, the input and the output set of vectors are non-contradictory for a successful training and operational function.

The following section explains the use of ANN-BPN to determine the voltages of a radial distribution system.

IV. ANN-BPN IMPLEMENTATION FOR DETERMINING LOAD FLOW SOLUTION

The input vector for the ANN-BPN is the reap power and reactive power loads at various buses of power system. Therefore,

$$X = [P_1, P_2, P_3, \ldots\ldots P_n; Q_1, Q_2, Q_3 \ldots\ldots Q_n] \quad (1)$$

Here, P_i and Q_i are the real and reactive power loads at the i^{th} bus of the RDS and 'n' is the number of buses in the RDS.

By using this scheme several sets of loads were created:

1. By varying real and reactive power loads simultaneously at all load buses of RDS.
2. By varying both the real and reactive power loads simultaneously at a single load bus of the RDS

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3. By varying only the real power load at a single load bus of the RDS.
4. By only varying the reactive power load at single load bus of the RDS.

The k^{th} such load so generated is referred to by the vector X^k. Similarly the corresponding output vector for k^{th} input referred to O^k. the output vector refers to the bus voltages magnitude and the corresponding angle. Summarizing, several of these sets of input and output vectors are generated using the above method and are stored. After the successful training of the ANN-BPN it should be able to produce the bus voltage magnitude and phase angle for any of the input load pattern with maximum accuracy and minimum time.

The next section, the application of the analysis and the results of the proposed technique of determining load flow solution is discussed.

V. Results of the System Study

The proposed approach has been tested for 33 bus radial distribution system (Fig.5) using MATLAB environment. By using the Ladder Iterative Technique as explained in section II, the power flow equations were solved. Approximately 150 input and output vector pairs were generated for considering 33-bus system, in order to achieve a broad representation of the power system in the ANN-BPN. The BPN was trained and the results are as shown in fig.6. and the output voltages of BPN can be seen in fig.7.

And hence, the ANN-BPN is ready to use. The results from the actual load flow solution and from the training ANN for a particular pattern is shown in Table I. the method seems to be fast and found to be very efficient. It works well and smooth.

VI. Conclusion

The novel approach in this paper presents a well defined technique to determine the load flow solution of a radial distribution system, which is simple to implement and efficient in computation. Several load pairs were considered and their solution was assessed using the conventional method of Ladder Iterative technique. Then using these pairs of input and target vector sets, the ANN-Backpropagation Network is trained. Thereafter, the BPN is ready for use wherein, given a load, it gives out the voltage solution in minimum time and maximum accuracy. The proposed reconfiguration method is tested on the standard 33-bus RDS and results demonstrate the effectiveness of the proposed method.

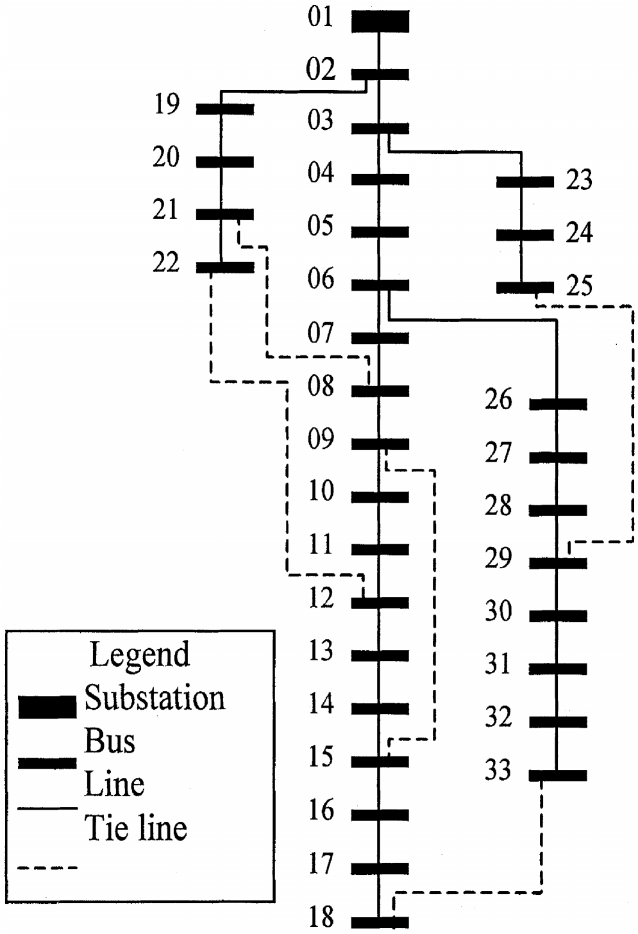

Fig.5. The 33-bus radial distribution system.

TABLE I
Comparison Of results from Conventional method and ANN-BPN

Line No.	Sending Bus	Receiving Bus	Load at receiving End Bus (Test Input)		Solution From BPN		Expected Solution (Solution from Ladder Iterative technique)		Accuracy (%)
			Real Power (P) (kW)	Reactive power (Q) (kVAr)	Voltage Mag. (pu)	Phase Angle (rads)	Voltage Mag. (pu)	Phase Angle (rads)	
1	1 Main SS	2	100	60	1.00	0.00	1.00	0.00	100
2	2	3	90	40	0.99	0.00	0.99	0.00	99.99
3	3	4	120	80	0.98	0.01	0.98	0.01	99.98
4	4	5	60	30	0.96	0.01	0.96	0.01	99.91
5	5	6	60	20	0.95	0.02	0.95	0.02	99.87
6	6	7	200	100	0.95	0.02	0.95	0.02	99.92

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7	7	8	200	100	0.93	0.01	0.93	0.01	99.61
8	8	9	60	20	0.92	0.01	0.92	0.01	99.97
9	9	10	60	20	0.92	0.01	0.92	0.01	99.68
10	10	11	45	30	0.91	0.01	0.91	0.01	99.23
11	11	12	60	35	0.91	0.01	0.91	0.01	99.47
12	12	13	60	35	0.92	0.01	0.92	0.01	99.36
13	13	14	120	80	0.92	0.01	0.92	0.01	99.24
14	14	15	60	10	0.92	0.01	0.92	0.01	99.23
15	15	16	60	20	0.92	0.01	0.92	0.01	99.15
16	16	17	60	20	0.92	0.01	0.92	0.01	99.58
17	17	18	90	40	0.92	0.01	0.92	0.01	99.78
18	2	19	90	40	0.92	0.01	0.92	0.01	99.14
19	19	20	90	40	0.92	0.00	0.92	0.00	99.55
20	20	21	90	40	0.90	0.00	0.90	0.00	99.59
21	21	22	90	40	0.90	0.00	0.90	0.00	99.95
22	3	23	90	50	0.90	0.00	0.90	0.00	99.87
23	23	24	420	200	0.99	0.00	0.99	0.00	99.99
24	24	25	420	200	0.99	0.00	0.99	0.00	99.91
25	6	26	60	25	0.99	0.00	0.99	0.00	99.71
26	26	27	60	25	0.98	0.02	0.98	0.02	99.32
27	27	28	60	20	0.97	0.02	0.97	0.02	99.33
28	28	29	120	70	0.96	0.02	0.96	0.02	99.27
29	29	30	200	600	0.94	0.02	0.94	0.02	99.71
30	30	31	150	70	0.93	0.03	0.93	0.03	99.71
31	31	32	210	100	0.92	0.03	0.92	0.03	99.19
32	32	33	60	40	0.92	0.02	0.91	0.02	98.71
Substation Voltage=12.66kV									

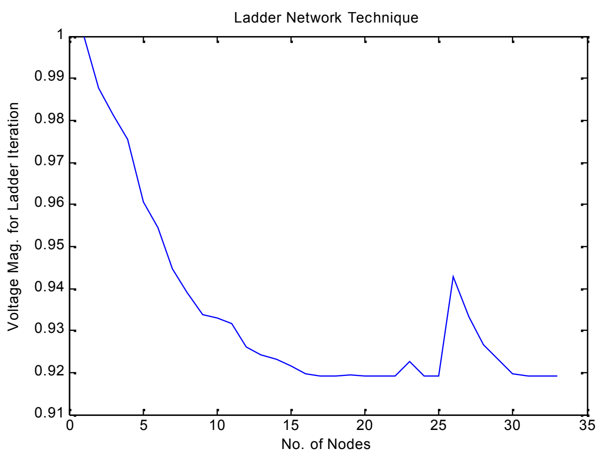

Fig.6. Ladder Iterative Voltage magnitude

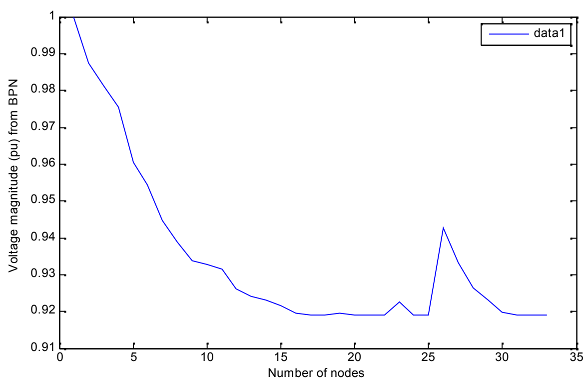

Fig.6. BPN Voltage magnitudes after training

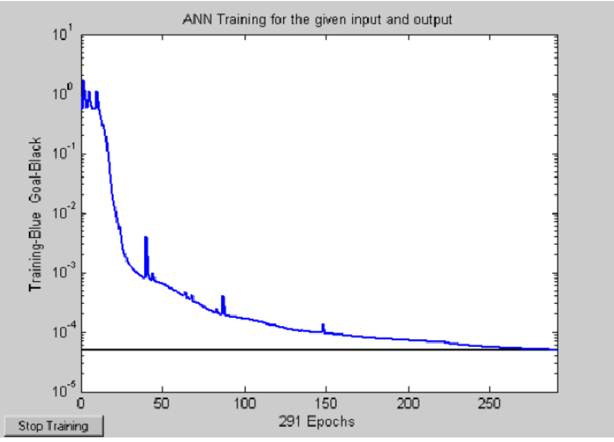

Fig.7. Training results ANN-BPN

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