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Prediction of Optimum Gas Mixture for Highest SXR Intensity Emitted by a 4kj Plasma Focus Device Using Artificial Neural Network

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Abstract

In this study, artificial neural network (ANN) is investigated to predict the optimum gas mixture for highest soft X-ray (SXR) intensity emitted by a 4kJ plasma focus device. To do this multi-layer perceptron (MLP) neural network is used for developing the ANN model in MATLAB 7.0.4 software. In this model, the input parameters are voltage, Percentage of nitrogen in admixture and pressure and the output is SXR intensity. The obtained results show that the proposed ANN model has achieved good agreement with the experimental data and has a small error between the estimated and experimental values. Therefore, this model is a useful, reliable, fast and cheap tool to predict the optimum gas mixture for highest SXR intensity emitted by plasma focus devices.

Keywords: Plasma Focus; ANN; MLP; Soft X-Ray; Highest Intensity.

Introduction

Plasma focus devicesmake use of a self-generated magnetic field to compress a plasma to very high densitiesand high temperatures within a lifetime of about 50–100 ns [1]. In a plasma focus device (PF), the capacitor is charged and the voltage is transferred across the electrode assembly using the spark gap switch, resulting in gas breakdown at the closed end. The current sheath then accelerates towards the open end of the anode in the axial acceleration phase. Finally, it slides across the face of the anode in the radially inward direction to form a hot and dense plasma column at the top of the anode. The radial collapse phase plays the most important role in the plasma focus evolution due to its extremely high energy density, its transient character and its being a rich source of phenomena like emission of intense radiation, high energy particles and copious nuclear fusion products. The electron–ion interaction processes such as bremsstrahlung, recombination emission and line emission are considered to be responsible for the emission of soft thermal x-rays from hot and dense focused plasma columns [1]. The potential of a plasma focus device as an intense soft x-ray source [2] has been the motivation for intense studies in the past few years; attempts have been made to optimum the X- ray yield by adjusting various parameters such as discharge energy, operating voltage, filling pressure and different machine parameters [3]-[7].

The device operated with different gases has been used as an X-ray source for a variety of applications such as X – ray microscopy [8], Micromachining [9],imaging of thin biological samples [10], X-ray backlighting [11] and X-ray lithography[12].From the viewpoint of the past works, it is clear that theappropriate choice of various experimental parameters can enhance the X-ray yield to many folds in the PF device.

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One main part of investigation is SXR optimization by different gas mixtures. Gribkovet al. investigated the soft X-ray emissions by using pure argon and mixtures of argon with deuterium or krypton. They have found that the highest x-ray output has been achieved by operating the PF device in admixture of gases with volumetric ratios of 70:30 for Ar–Kr admixtures [8].Y. Kato et al. showed experimentally that plasma produced from a mixture of hydrogen and a rare gas such as neon, argon, or krypton is an effective source of a characteristic x- ray of the rare gas. It was found that maximum irradiance depends on the kind of rare gas used and the volumetric ratio of rare gas to hydrogen [13].M. Favreet al.reported successive compression peaks operating with H2–Ar admixture in the volumetric ratio of 40:60.Two main periods were observed in the X-ray emission, corresponding to two successive compressions in the focus [14].P. Silva and M. Favre investigated the properties of hotspots in plasma focus discharges operating in hydrogen–argon mixtures. The PF has been operated in different ratios,ranging from 5% to 20% argon. The operation of PF discharges with mixtures of hydrogen and heavier gases had been found to increase the emission efficiency and reproducibility of the plasma conditions, as compared with pure hydrogen operation. When the PF was operated in mixtures of hydrogen and argon, the higher argon content produced rather uniform hotspots, with a better than 80% axial localization [15].R. Verma et al. came into conclusion that about 17- and 10-fold increase in X-ray yield in spectral ranges of 0.9–1.6keV and 3.2–7.7keV, respectively, had been obtained with deuterium-krypton admixture at operating pressures of $\leqslant$ 0.4mbar[16].

Artificial neural network is a good technique used to handle problems of modeling, prediction, control, and classification. Over the last few years neural networks have been studied for potential applications in plasma processing [17].Neural networks were able to successfully predict disruptions in DIII–D tokamak [18].P. Jagos.et al. used neuralnetworks to analysis of experimental data in the PF device. A multilayer perceptron(MLP) trained with the back-propagation algorithm were used for the predictive modeling of the PF magnetic field signals [19].

In the present research,neural networks are used to predict optimum gas mixture forhighest SXR intensity. The advantage of this method is, when there is little empirical data, the optimum pressure for highest SXR emission on a wide range of pressures for different gas mixture can be obtained.Early, the behavior of the intensity of SXR emitted from different volumetric ratios of nitrogen: neon (N_2: Ne) gas mixture has been determined experimentally.

Experiments

The input to the neural network wasproduced by measurement of SXR emission in the APF plasma focus device.As it shown in fig.1, APF isa Mather-type plasma focus [20] charged by a capacitor bank of 36 μF which was fired at the applied voltages of 11, 12, and 13 kV. For volumetric ratios of nitrogen:neon (N_2: Ne) gas mixtures with the percentages of (50:50), (75:25), (90:10) and (100:0) were used as the working gases during the experiments. For X-ray measurement, aPIN-diode covered with Al +Mylar (12 μm) which has the maximum sensitivity in 3.3 KeV was used. According to this sensitivity curve one may infer easily that the characteristic neon line radiations which are mainly Ne Lyα (1s-2p, Ne: 12. 13 A° or 1022 eV) and Heα line ($1s^2$-1s2p, Ne: 13.44 A° or 922 eV) [21] do not normally generate any signal on the channel. The pin diode placed at 22 cm far from the upper end of the anode in the side-on direction.

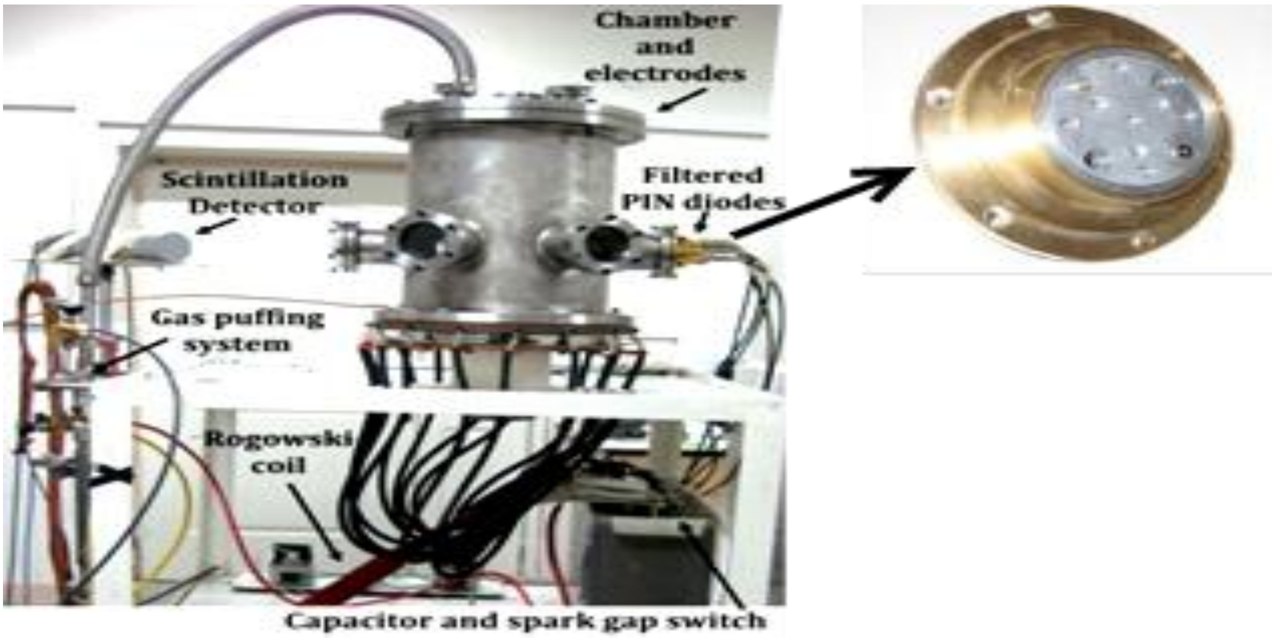

Fig. 1. Experimental setup and the diagnostics

Variations of SXR intensity (average area under the SXR signals of PIN-diode) with pressure at applied voltages 11, 12, and 13 kV is presented in Fig.2, for four used volumetric ratios.At voltage of 11 kV, for volumetric ratios (90:10) and (75:25) of (N_2: Ne) admixture, the optimumpressure is 3.5 Torrwhile for (50: 50) and (100: 0) volumetric ratios the optimum pressures are 4 and 2.5 Torr, respectively. The maximum area under the soft X-ray signal at 11kV for volumetric ratios of (100: 0), (90: 10), (75: 25) and (50: 50) are 2.77×10^{-7}, 4.69×10^{-7}, 5.12×10^{-7} and 7.12×10^{-7} V.s, respectively. This means the maximum area under the SXR signal is directly proportional to volumetric ratio of Ne gas. Maximum emission of SXR in admixture of nitrogenand neongases is higher than in pure nitrogen gas.Another important point to take note of is that at higher voltages, 12 and 13 kV, general behavior of PIN diode signals is the same as voltage 11 kV, but as it can be observed, the optimum pressures shift to higher values. For volumetric ratios (90:10) and (75:25) of (N_2: Ne) admixture, the optimum pressure is 4 Torr while for admixture with percentage of (50:50), the optimum pressures is 4.5 Torr. For pure nitrogen the optimum pressures are 3 and 3.5 Torr at 12 and 13 kV, respectively. The maximum area under the SXR signal at 12 kV for volumetric ratios of (50: 50), (75: 25), (90: 10) and (100: 0) are 14.3×10^{-7}, 9.06×10^{-7}, 6.64×10^{-7}, 6.06×10^{-7} V. s, respectively.

As mentioned above the intensity of SXR increases with the increase of neon (Ne) percentage in the admixture of (N_2: Ne). For all different working admixture gases, intensity of SXR increases with increasing in the applied voltage. Thus the highest intensity was for the volumetric ratio of (50:50) operating at the voltage of 13 kV. The maximum area under the SXR signal at 13 kV for volumetric ratios of (50: 50), (75: 25), (90: 10) and (100: 0) are 27.34×10^{-7}, 19.12×10^{-7}, 10.4×10^{-7} and 6.42×10^{-7} V. s, respectively.

At all voltages, for volumetric ratio (50:50) of (N_2: Ne) mixture, the optimum pressures are observed at higher amounts. The reason is that neon gas (Ne) is lighter than nitrogen gas (N_2).Significant amount of neon (Ne) in the working gas admixture causes the plasma sheath arrives at the anode top before the first maximum in discharge current, thus the maximum compression is at lower current. With increment in the pressure, the peak current synchronizes with the pinch formation.

Logically, the increase in gas pressures leads to the slowing down of the current sheath in the axial acceleration phase and at an optimum gas pressure the radial collapse phase occurs closer to (or at) current maximum resulting in the efficient heating of the pinch plasma column due to joule heating. With the increase in pressure, the plasma density also increases and hence would also contribute to an increase in the SXR yield. But, after a certain critical pressure the axial transit time increases further and hence the collapse phase occurs much after the current maximumresulting the decrease in the SXR yield.

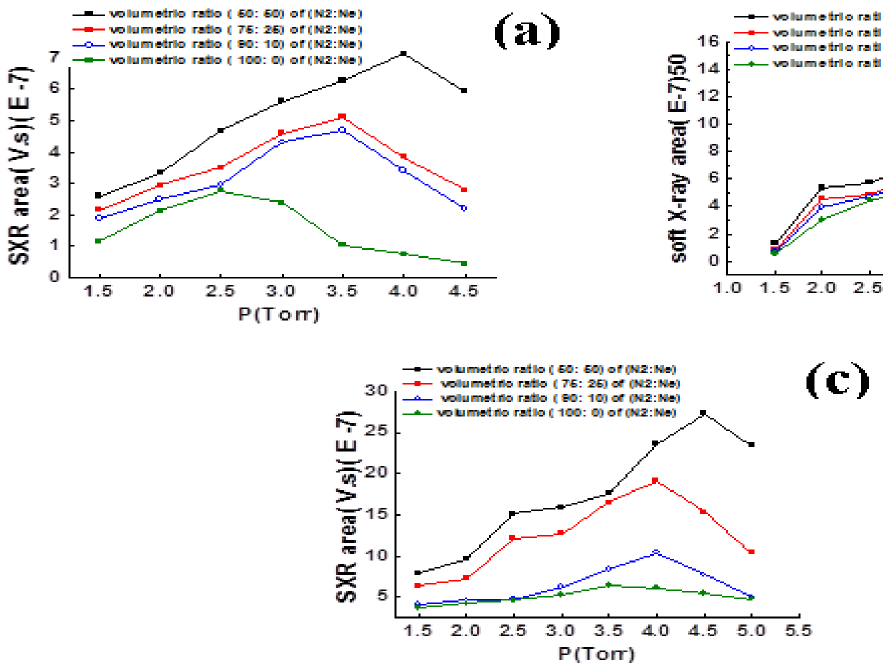

Fig. 2.Soft X-ray intensity for four used volumetric ratios (50:50), (75:25), (90:10) and (100: 0) of (N_2: Ne) at: **(a)** 11 kV, **(b):**12kV, and **(c):**13kV

Modeling Approach

An ANN is based on the operation of biological neural networks. The fundamental processing element of ANN is an artificial neuron [22]. Multi-layer perceptron (MLP) networks are the most widely used ANNs [23]. The simplified overview of the proposed MLP model is shown in Fig.3, where the inputs are voltage (kV), percentage of nitrogen in admixture and pressure (torr) and the output is SXR intensity (V. s).

The output from *ith* neuron of the first hidden layer is given by:

$$U_i = f\left(\sum_{k=1}^{3}(x_k W_{ki}) + b_i\right) \qquad i = 1,2,....,7 \tag{1}$$

The output of the *jth* neuron in the second hidden layer is given by:

$$Z_j = f\left(\sum_{k=1}^{7}(U_k W_{kj}) + b_j\right) \qquad j = 1,2,....,9 \tag{2}$$

The output of the neuron in the output layer is given by:

$$O = \sum_{k=1}^{9}(Z_k W_k) + b \tag{3}$$

Where *x* is the inputs, *b* is the bias term, *W* is the weighting factor and *f* is the activation function of the hidden layers.

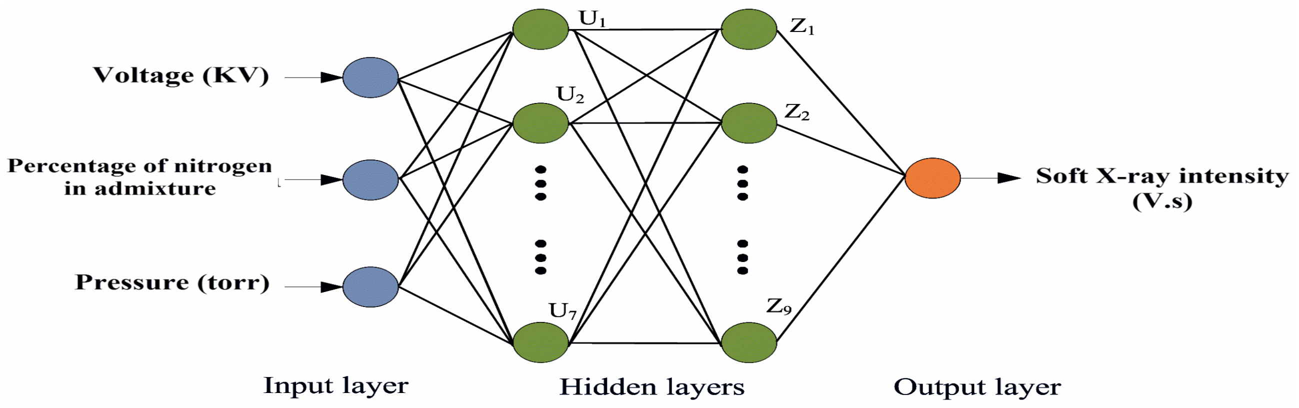

Fig.3. The proposed ANN model.

The data set required for training the network is obtained using the experimental study. The number of samples for training and testing data are 61 (about 76%) and 19 (about 24%) respectively. In this study, different ANN structures were tested and optimized to obtain the best ANN configuration. We tested many different structures with two, three, and four hidden layers with different number of neurons in each layer. Table 1 shows the specification of the best proposed ANN model.

Table 1.Specification of the best proposed ANN model.

Neural network	**MLP**
Number of hidden layer	2
Number of neurons in the input layer	3
Number of neurons in the first hidden layer	7
Number of neurons in the second hidden layer	9
Number of neurons in the output layer	1
Learning rate	0.5
Number of epochs	300
Adaption learning function	Trainlm
Activation function	Tansig

Theoretical Results and Discussions

Fig.4 shows the comparison between the experimental and predicted results using the proposed ANN model for training and testing data. The Comparison between experimental and predicted (ANN) results for testing data is shown in Table 2.

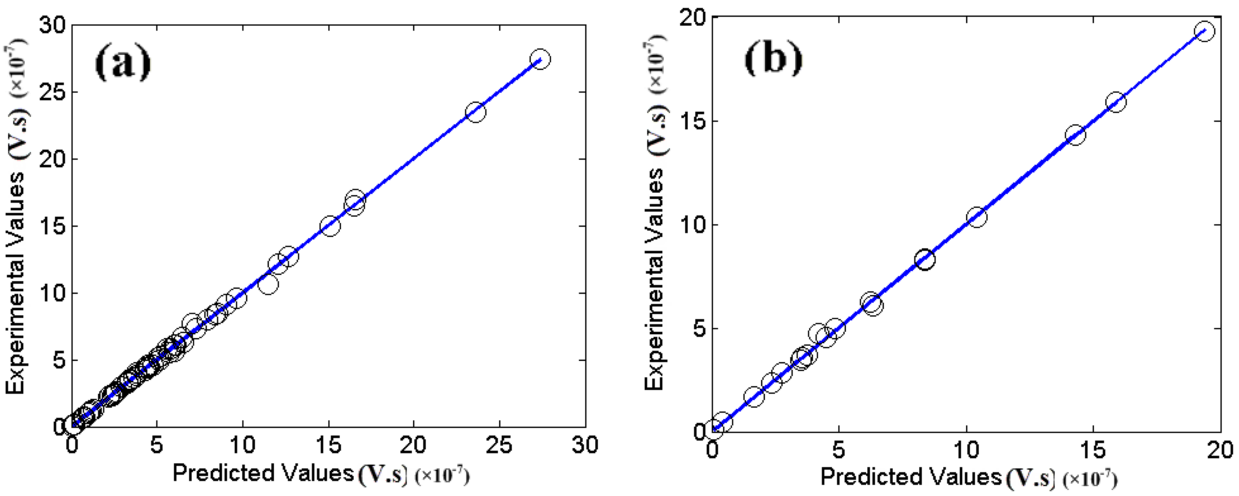

Fig. 4. The Comparison of the proposed ANN model with the experimental data:**Left)**forthe output of the training data, **Right)**for the output of the testing data.

Table 2.The Comparison between experimental and predicted (ANN) results for testing data.

Voltage (KV)	Percentage of nitrogen in admixture	Pressure (torr)		Soft X-ray (V.s) ($\times 10^{-7}$)	
				Experimental	ANN
11	50	3		1.68	1.660791605
11	75	1.5		2.34	2.333671316
11	75	3.5		3.5	3.425388966
11	90	2		2.78	2.823164401
11	90	4		4.51	4.517933136
11	100	2.5		3.77	3.703665612
11	100	4.5		0.433	0.431711195
12	50	3		14.3	14.29384616
12	75	1.5		6.23	6.254620325
12	75	3.5		4.83	4.961734804
12	90	2		3.57	3.571238064
12	90	4		4.2	4.701955136
12	100	2.5		8.38	8.327489687
12	100	4.5		0.0991	0.099904405
13	50	3		15.9	15.87001129
13	75	1.5		6.35	6.037913531
13	75	3.5		19.4	19.31935196
13	90	2		8.36	8.238167666
13	90	4		10.4	10.33227919

Table 3 shows the obtained errors for the proposed ANN model, where the mean relative error percentage (MRE %), the mean absolute error percentage (MAE %), the root mean square error (RMSE), and the correlation factor (CF) of the proposed ANN models are calculated by:

$$\mathrm{MRE}\% = 100 \times \frac{1}{N}\sum_{i=1}^{N}\left|\frac{X_i(\mathrm{Exp}) - X_i(\mathrm{Pred})}{X_i(\mathrm{Exp})}\right| \qquad (4)$$

$$\mathrm{MAE}\% = 100 \times \frac{1}{N}\sum_{i=1}^{Z}\left|X_i(\mathrm{Exp}) - X_i(\mathrm{Pred})\right| \qquad (5)$$

$$\mathrm{RMSE} = \left[\frac{\sum_{i=1}^{N}(X_i(\mathrm{Exp}) - X_i(\mathrm{Pred}))^2}{N}\right]^{0.5} \qquad (6)$$

$$\mathrm{CF} = 1 - \left[\frac{\sum_{i=1}^{N}(X_i(\mathrm{Exp}) - X_i(\mathrm{Pred}))^2}{\sum_{i=1}^{N}(X_i(\mathrm{Exp}))^2}\right] \qquad (7)$$

where N is the number of data and ‘*X(Exp)*’ and ‘*X*(*Pred)*’ stand for experimental and predicted (ANN) values respectively.

Table 3.The obtained errors for the proposed ANN model.

Error	**Data**		
	Train	Test	
MAE	0.088	0.081	
RMSE	0.174	0.146	
MRE%	1.48	1.66	
CF	0.99946	0.99960	

Fig.4, Table 2 and Table 3 it is clear that there is a good agreement between the experimental and predicted values with minimum error for the output parameter. Fig.5, Fig.6 and Fig.7 show the obtained SXR intensity using the proposed ANN model for Voltage=11, 12 and 13 respectively. The maximum SXR intensities obtained from Figures 5, 6, and 7 are: $12.22 \times 10^{-7}, 14.32 \times 10^{-7}and34.93 \times 10^{-7}$ $(V.s)$, in (Voltage, percentage of nitrogen in admixture, Pressure)=(11kV, 58%, 2.1 Torr), (12 kV,50%,3Torr) and (13 kV,73%,3.3Torr) respectively. From these results, it is clear that the proposed ANN model can be used as an accurate model to prediction of the optimum gas mixture for highest SXR intensity emitted by a plasma focus device.

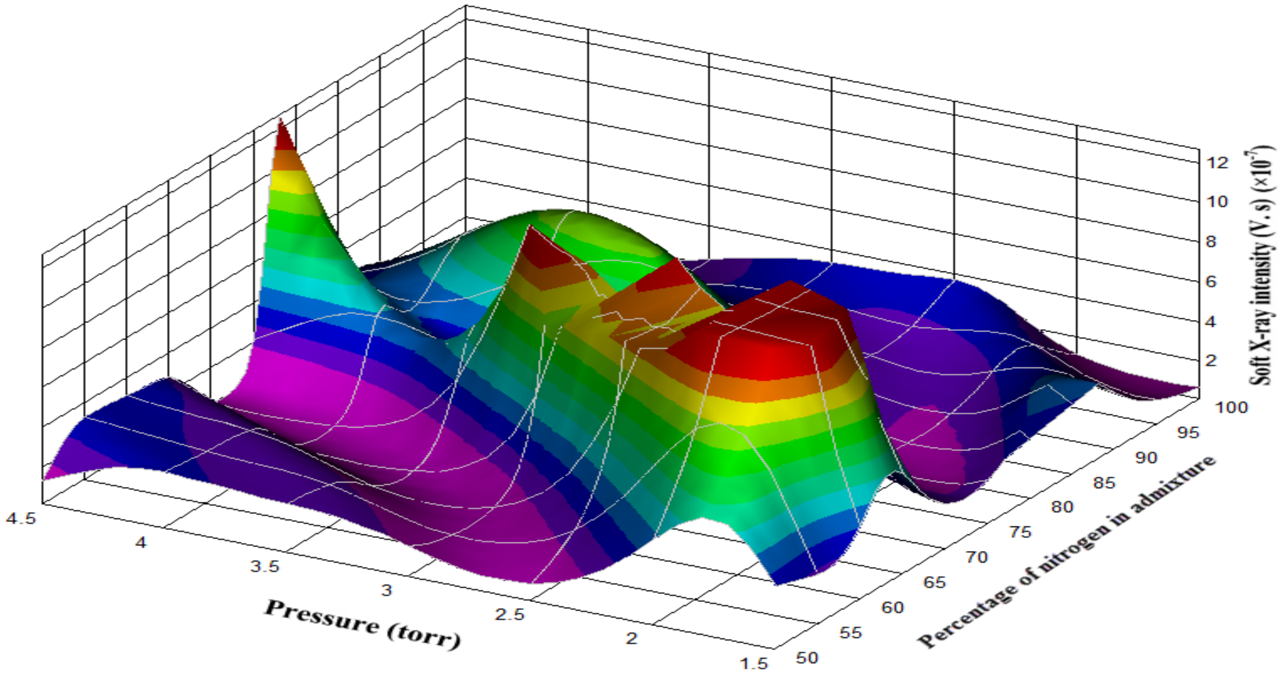

Fig.5.The obtained soft X-Ray intensity using the proposed ANFIS model for Voltage11 kV.

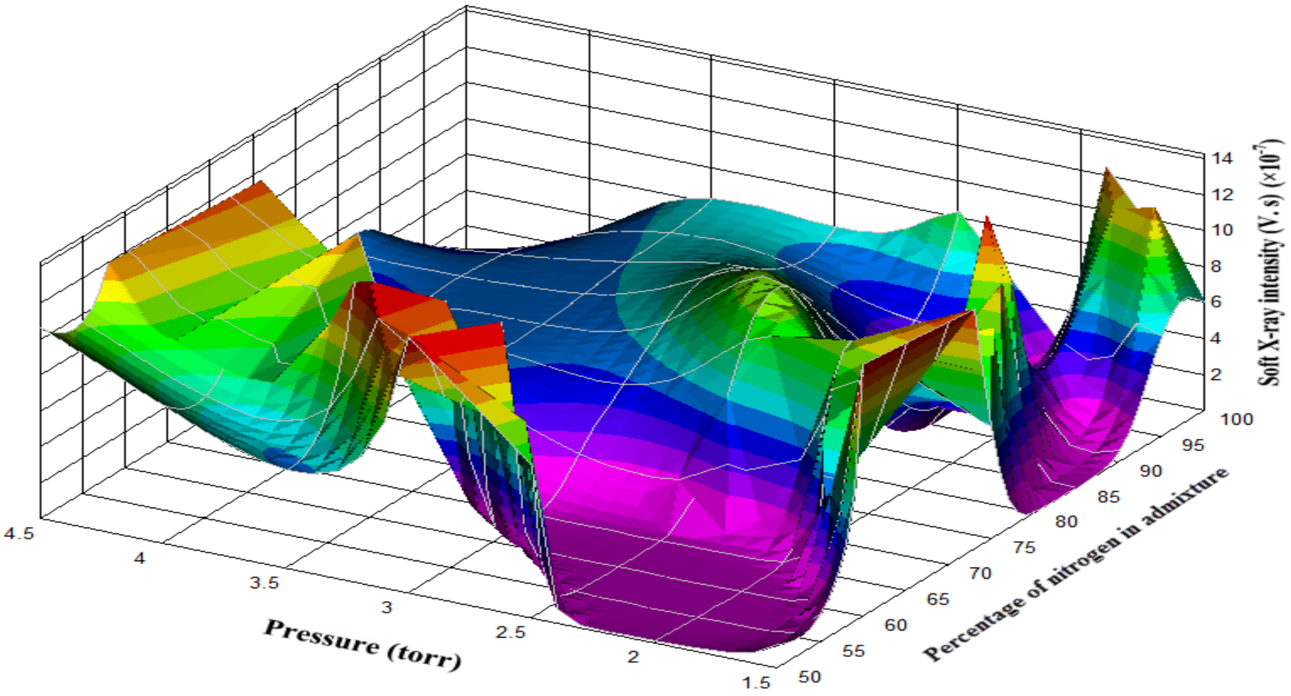

Fig. 6.The obtained soft X-Ray intensity using the proposed ANFIS model for Voltage12 kV.

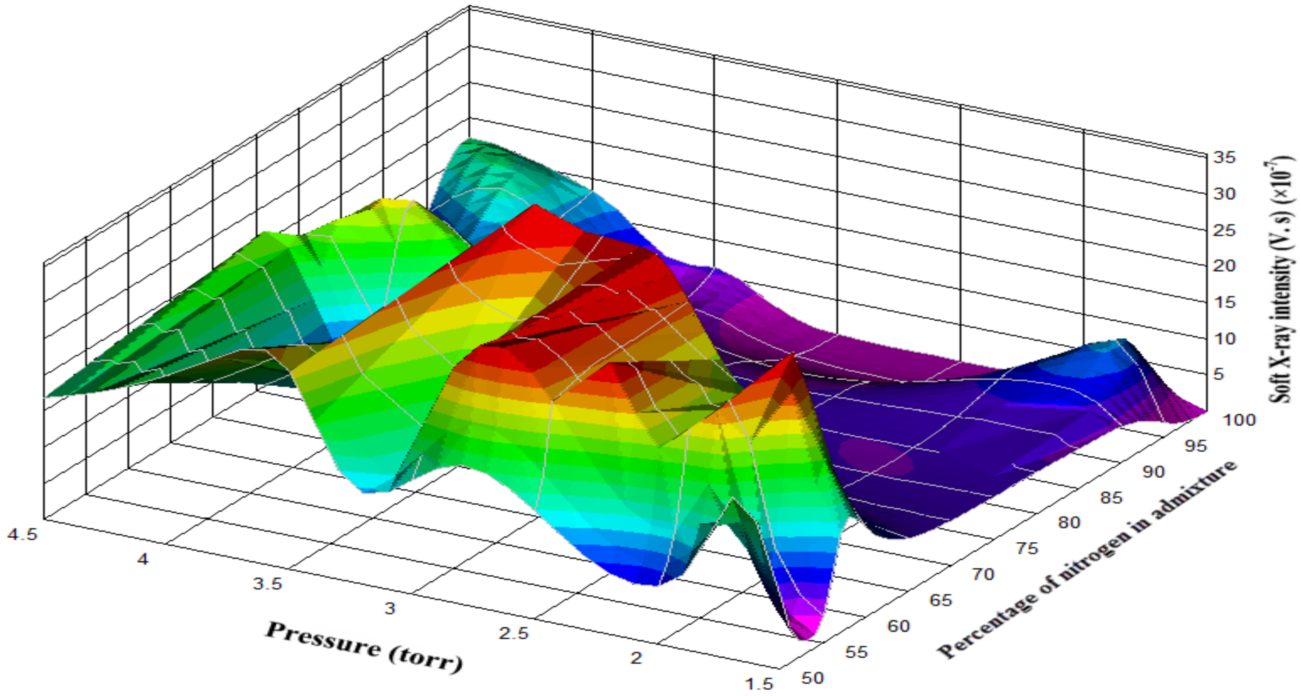

Fig. 7.The obtained soft X-Ray intensity using the proposed ANFIS model for Voltage13 kV.

Conclusion

In this paper, the applicability of artificial neural networkfor prediction of the optimum gas mixture for highest SXR intensity emitted by a 4kJ plasma focus device is presented. Multi-layer perceptron neural network is used for developing the ANN model. The obtained results show that the proposed ANN model has achieved good agreement with the experimental data with minimum error. Also, the results show that this model is a useful, reliable and fast tool to predict the optimum gas mixture for highest SXR intensity.

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