X-parameter modelling of GaN HEMT based on neural network

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Abstract: Currently, S-parameters are commonly used in the design, measurement, and modelling of microwave circuits, but it is only suitable for linear small-signal conditions and not suitable for large-signal conditions. X-parameter is more accurate than the S-parameter in characterising the non-linearity of the device or the microwave circuit, and the artificial neural network has significant advantages in predicting the non-linearity of the system. Based on theoretical analysis, this article selects the GaN HEMT device CGH40010F for X-parameter modelling. Using X-parameter generator of ADS software, the X-parameters of the device were obtained. An X-parameter model based on BP neural network was built using MATLAB neural network box. The accuracy of the model was verified by comparing the test data with the model prediction data.

1 Introduction

In the field of microwave radio frequency, with the increasing power of the input signal, the device gradually works from linear to non-linear region, shows the large signal characteristic [1, 2]. S-parameter representing the linear characteristic cannot accurately describe the large signal characteristic of the device [3, 4]. Therefore, the research on non-linear characteristics of networks has become a hot research topic.

In recent years, there have been many studies on large-signal modelling, using a variety of methods to characterise the non-linear characteristics of the device [5, 6], such as non-linear scattering parameters, X-parameters, and artificial neural network methods. The non-linear scattering parameters obtained by the S-parameter expansion is easy to understand and convenient to use in the cascade. X-parameter also serves as an extension of the S parameter. Unlike the non-linear scattering parameter, it takes into account the effect of the conjugate signal and is widely used because of its high accuracy [7, 8]. Artificial neural networks have significant advantages in predicting the non-linearity of the system, so learning about artificial neural network modelling techniques has also become a key point. Domestically, the modelling work for X-parameters has been carried out relatively late. More about the theory of X-parameter behavioural models and the improvement of algorithms. Therefore, it is worthwhile to establish an X-parameter behavioural model that can characterise large-signal operating characteristics based on the actual operating characteristics of the device.

2 Generation of X parameters of GaN HEMT devices

When actually designing a radio frequency circuit, the microwave system mostly operates in a non-linear working area instead of a theoretical linear area [9]. For example, when designing circuits such as frequency multipliers, mixers, and power amplifiers, the output signals of these devices include harmonics and cross-modulation components. The use of S-parameters to describe the circuit characteristics of the device is not accurate enough. X-parameter is used as the theoretical extension of the S-parameter in order to characterise the circuit characteristics of the device at large signal operating points and to describe the non-linear behaviour of the device more accurately [10, 11]. X-parameter theoretically describes the relationship between the reflected wave and the incident wave of frequency and the harmonics under the non-linear condition of the two port network.

In order to fully describe the non-linear behaviour of GaN HEMT devices, the DC behaviour of the device needs to be added, so a complete equation set can be obtained to describe the characteristics of the device.

\[
B_{p,k} = F_k \left[ \text{refLSOPS} \left\{ A_{p,k} \left( \frac{1}{q}, \frac{1}{k} \right) \right\}^p \right]^{\frac{1}{q}}
\]

where \(X_{p,k,l}^{FP}(\text{refLSOPS})\) represents the contribution of the input large signal to the output signal, \(X_{p,k,l}^{FP}(\text{refLSOPS})\) and \(X_{p,k,l}^{FP}(\text{refLSOPS})\) are the real and imaginary parts of X-parameter, respectively, providing the contribution of signal at input port \(q\) with \(l\)th harmonic to the signal at output port \(p\) with \(k\)th harmonic. \(Y_{p,k}^{P}(\text{refLSOPS})\) is the DC current X-parameter entry for large input signals at input port \(p\), and \(Y_{p,k}^{P}(\text{refLSOPS})\) provides the contribution of small-signals at input port \(q\) with \(l\)th harmonic to DC current at output port \(p\).

This article uses ADS software to extract X-parameters. Given a voltage bias suitable for the device's operation, input the frequency, and other conditions to X-parameter generator's application to obtain X-parameter of the GaN HEMT device, which will result in a file with the suffix name XNP. Fig. 1 shows the schematic of X-parameter generation for GaN HEMT devices.
i. The input frequency is from 1 to 5 GHz, and the step length is set to 1 GHz;
ii. Single-tone input signal power from 27 to 36 dBm, step length set to 3 dBm;
iii. The bias voltage Vgs is from −3.9 to −0.9 V, and the step length is set to 1 V;
iv. The bias voltage Vds is from 4 to 16 V and the step length is set to 4 V.

As shown in Fig. 2, X-parameter generated at the operating frequency of 1 GHz, the input signal power of 27 dBm, the bias voltage Vgs of −3.9 V, and the bias voltage Vds of 4 V is given. Due to space limitations, this section intercepts the contents of some X-parameters and uses the same method to obtain independent load traction simulation X-parameter [13, 14] 320 groups with different frequencies and bias voltages, in preparation for the subsequent X-parameter modelling.
3.1 Establishment of a network model

Fig. 3 shows an X-parameter network model based on BP neural network and is a three-layer BP network. The network consists of an input layer, a hidden layer, and an output layer. Each layer contains multiple neurons. The non-linear transfer function of each neuron generally adopts the Sigmoid function.

The four items of the bias voltages $V_{gs}$ and $V_{ds}$, the input power, and the frequency are used as the input items of the network. The 183 X-parameter items obtained by the X-parameter generator in the ADS are used as the output items of the network. The number of neurons in the hidden layer is more dependent on experience and determined by trial and error. The number of hidden layers should be set appropriately. If the number is too large, it will affect the learning of the network and reduce the performance. The following three formulas can be used as the reference formula for selecting the optimal number of hidden layer units, and the selection of the number of hidden layers can be accomplished by combining trial and error methods.

\[
l < n - 1 \\
1 < \sqrt{m + n + a} \\
l = \log_2(n)
\]  

(3)

Among them, $n$ is the input node, $l$ is the number of hidden layer neurons, $m$ is the output layer node.

According to the formula (3), the initial value of the neurons in the hidden layer is calculated as 28. In the subsequent network training, trial and error method can be used to continuously change the number of neurons in the hidden layer, and the optimal hidden layer neurons are determined according to the MSE and $R$ of the mean square error.

3.2 Network data training

Based on the BP network X-parameter modelling, it is essentially to establish a mapping relationship between four inputs and 183 outputs, which belongs to the function fitting problem. As LM algorithm converges quickly and is suitable for large-scale networks [15], this paper chooses LM algorithm for training.

3.3 Network prediction and model validation

The previous section completed the BP neural network modelling of X-parameters. After the model is established, the network needs to be predicted, and the correctness of the model is judged according to the error value of the target output corresponding to the predicted output of the network and the actual sample.

The following function can be used to predict the output of the network, in the form of

\[ y_{out} = \text{sim}(\text{net}, x) \]  

(4)

In the formula, net is the name of the well-designed network simulink module, $x$ is the input of the network, and $y_{out}$ is the output predicted by the network. The obtained network output $y_{out}$ is compared with the X-parameter generated by the ADS to obtain the error matrix error. Five groups of data were analysed.

For the error matrix error of the model to draw a three-dimensional surface map, the error matrix is a 183*320 matrix, and the memory requirement is higher when drawing the 3D surface. Therefore, this paper selects five sets of data, using the mesh command in MATLAB for 3D drawing, X-axis is integer from 1 to 5, Y-axis is integer from 1 to 183, and Z-axis is the error value, and the 3D surface map shown in Fig. 4 is obtained. You can see the Z-axis of the entire surface, that is, the error value of each X-parameter item is <0.1.

The left side shown in Fig. 4 is a set of output error curves, which can be drawn in the two-dimensional plane as shown in Fig. 5. It can be seen that the output error of a set of X-parameters is mainly concentrated in the interval $(-0.4, 0.4)$, indicating that the model is more accurate.

The BP network model can accurately reflect the non-linear characteristics of the device, so large signal X-parameters can be modelled. It can be used to verify the accuracy of measurement data, and then applied to the actual circuit design, such as power amplifier, frequency multiplier, and other circuit design.

4 Conclusion

Here, X-parameter modelling and neural network modelling are combined, and the bias voltage, input power, and frequency of the device are used as input terms. X-parameter term produced by ADS is used as the output item, and the BP network model is used

![Fig. 3 X-parameter network model](image1)

![Fig. 4 X-parameter model error three-dimensional map](image2)
for learning and training, and the BP network model of X-parameters is established. The Simulink simulation module is generated by the model to get the black box model of X-parameter, then the output of the network model is predicted by the formula (4), and the error graph can be obtained. Comparing the output of the model with the expected output can get the error graph. The smaller error indicates that the obtained network model is more accurate.

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6 References

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