

Multi-objective Agent Model for XGBoost Controlled VFTO Simulator Based on Bayesian Optimization Algorithm

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Abstract. VFTO generated from GIS may cause interference and damage to terminal equipment on the primary and secondary sides, but experimental measures to evaluate the affected equipment and electromagnetic effects of the equipment through actual measurements are quite limited, so it is desired to build a VFTO simulator in the laboratory for experimental research and laboratory testing. Most of the current researches are conducted by building a true-type experimental platform for VFTO simulation, but this method has the disadvantages of large footprint, high cost and the scope of application can only simulate VFTO in a certain situation. Therefore, this paper establishes a broadband circuit model considering the pulse generator and the frequency domain equivalent transmission line model, and introduces the machine learning algorithm XGBoost to fit the agent model of the functional relationship between the design target and the structural parameters by establishing the sample data of the input circuit parameters and the output frequency waveform characteristics of the simulator, which is capable of dynamically adjusting the input parameters based on the waveform characteristics according to the changes of the target waveform, and ensures that a controllable waveform is obtained accurately in the laboratory the accuracy of obtaining controllable waveforms, thus realizing the output of controllable analog VFTO waveforms by changing the parameters of circuit components. Finally, the Bayesian optimization process is used for the hyper-parameter optimization of the XGBoost model, which has a fast convergence speed, and the characteristics of the output model are compared and analyzed, which verifies the feasibility and superiority of the proposed agent model as well as the multi-objective optimization method.

Keywords: VFTO; Agent model; XGBoost; Bayesian optimization.

1. Introduction

The GIS encounters extraordinarily fast transient processes during switching operations, which can form fast transient overvoltages (VFTO), seriously affecting the safe operation of the internal equipment, externally connected equipment, and secondary equipment of the GIS[1]. At present, there are two main methods to simulate the generation of VFTO, one is to use the actual GIS disconnecting switch structure for switching operations to generate VFTO, but the resulting VFTO waveforms have a random nature, can only simulate a specified VFTO waveforms, the resulting waveforms are not good and due to the large footprint and other characteristics of the higher cost; the other method is to build the VFTO simulation generator to generate ultrafast transient processes[2]. The other method is to use a built VFTO simulator to generate extra fast transient processes[3]. The VFTO simulator built in the laboratory using damped oscillation has the advantages of flexible adjustable parameters, easy to control the output waveform, and does not require the entire pipeline to be energized, which has less insulation requirements.

Combined with the current engineering problems, this paper introduces a VFTO simulator for experimental research and laboratory testing, and establishes a broadband circuit model considering the Marx pulse generator and the frequency domain equivalent transmission line model. There is an optimization problem due to the correlation between the parameters of individual circuit elements. Therefore, based on the broadband circuit model, a proxy model with automatic differentiation capability that can directly solve the gradient in high-dimensional space is used. By introducing the machine learning algorithm XGBoost to establish the proxy model between the input circuit

element parameters and the output waveform features in the broadband circuit model, and carrying out a multi-objective optimization design of the proxy model, which can withstand the burden of calling the values many times, efficiently solves the batch processing of the data And greatly reduce the time and complexity of the calculation, so as to achieve the change of circuit component parameters to achieve controllable output analog VFTO waveforms.

2. Broadband circuit modeling

2.1 Circuit Theory Techniques

The VFTO waveforms that are more commonly generated in laboratory build simulations are pulsed power system devices consisting of a Marx generator and an equivalent transmission line with a Marx generator structure at the first section and a transmission line with load model consisting of the electrical system inside the device at the end[4][5]. From the initial end of the transmission line to the distance under study, a series of lumped components form the transmission line equivalent circuit model. The uniform transmission line equation can be derived from Kirchhoff's law.

The solution for the voltage and current at a distance from x' the terminals of the transmission line is:

$$\begin{bmatrix} \dot{U} \\ \dot{I} \end{bmatrix} = \begin{bmatrix} \cos \frac{wx'}{v} & jZ_c \sin \frac{wx'}{v} \\ j \frac{1}{Z_c} \sin \frac{wx'}{v} & \cos \frac{wx'}{v} \end{bmatrix} \begin{bmatrix} U_0 \\ I_0 \end{bmatrix} \quad (1)$$

$Z_c = \sqrt{\frac{L_0}{C_0}}$ and $\gamma = jw\sqrt{L_0C_0}$ are the lossless transmission line characteristic impedance and propagation constant.

2.2 VFTO Characterization

Since the VFTO is a cluster of pulses generated by multiple repeated breakdowns of the gas gap of the isolation switch, its frequency characteristics are mainly affected by the length of the GIS busbar operated by the isolation switch, the size of the GIS structure, the value of the arc resistance, etc., and the frequency components are very numerous[6][7]. The main frequency characteristics of the VFTO are the low-frequency component formed by the oscillation of the circuit loop formed by the inductance and capacitance inside the device and the power supply and the ultrahigh-frequency component formed by the isolation switch Contact gap breakdown with the GIS internal system devices constitute the equivalent capacitance, inductance and switch on both sides of the short bus back and forth oscillation of the formation of ultra-high-frequency components near 10MHz.

Therefore, in this paper, the modeling objective is to achieve the simulated multi-resonance VFTO spectrum in the 10MHz band.

2.3 VFTO simulator structure and output

Figure 1 shows a general schematic of the proposed VFTO simulator, including the Marx pulse generator, simulated GIS pipeline, and end loads. The pulse generator utilizes Marx circuitry to produce high voltage bi-exponential nanosecond pulses that are introduced into the simulated GIS pipeline for reflection. This VFTO simulator is used for experimental research and laboratory testing, and a broadband circuit model considering the pulse generator and the frequency domain equivalent transmission line model is developed, see Figure 2, where the simulated VFTO waveforms can be adjusted by circuit parameters.

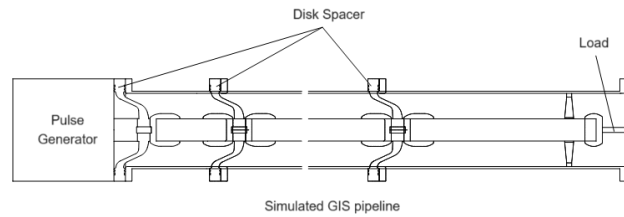


Figure. 1 Schematic of the proposed VFTO simulator

Based on the structure of the simulator and the principle of the Marx generator, an equivalent circuit model is developed, as shown in Figure 2. The Marx generator can be approximated as a capacitor, which is pre-charged to voltage U_0 for analysis, and the switch S is closed at the moment T_0 to observe the transient voltage waveform of the load.

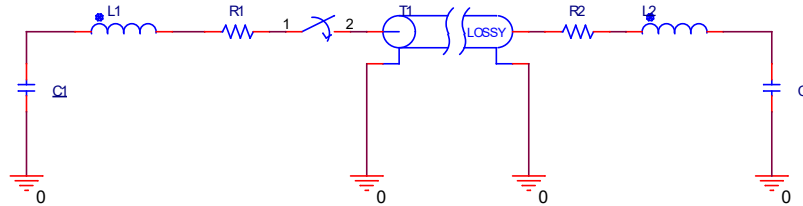


Figure 2: Equivalent circuit diagram of VFTO simulator

The above proposed broadband circuit model for VFTO simulation enables simulated multi-resonance VFTO spectra in the 10MHz band.

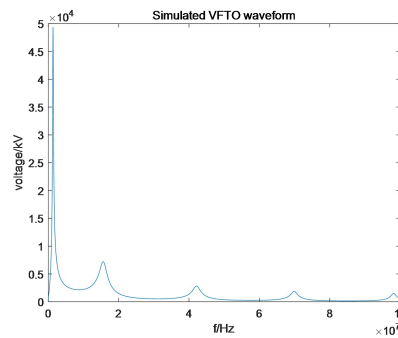


Figure 3: Simulated waveform

3. XGBoost-based agent model building

In the process of model building, because the output parameters selected by the agent model are waveform features, the relationship between the independent variable and the dependent variable can not be directly expressed, which is in the form of an implicit function, in order to improve the efficiency of the calculation, the reliability of the method of establishing the agent model through machine learning uses a large amount of data generated to construct a close to the real state relationship[8].

3.1 Introduction to the XGBoost algorithm

XGBoost is an optimized distributed boosting algorithm based on a tree model, which is widely used for classification and prediction due to its excellent results and performance[9]. Its objective function is:

$$\begin{aligned}
 \text{obj}^{(t)} &= \sum_{i=1}^n l(\hat{y}_i, y_i) + \sum_k \Omega f_k \\
 &= \gamma T + \sum_{j=1}^T \left[\sum_{i \in I_j} L(y_i, \hat{y}_i^{t-1} + w_j) + \frac{1}{2} \lambda \sum_{j=1}^T w_j^2 \right] \tag{2}
 \end{aligned}$$

γ, λ : hyperparameters to control the penalty strength; T: number of leaf nodes; $\hat{y}_i^{(K)}$ denotes the prediction result of sample x_i .

3.2 Data Acquisition and Preprocessing

The data set needed for the agent model is generated by the circuit model built above, a large number of simulated VFTO waveforms are generated by continuously changing the input circuit parameters in the circuit model, and the output parameters we need are obtained by extracting the waveform features, and the input and output parameters are combined into a data set, and the data are processed by normalization methods in order to eliminate the magnitude differences since the data are not in one order of magnitude [10]. . Some of the samples after processing are shown in Table 1. The feature scaling method used here is "linear function normalization".

$$X_{norm} = \frac{X - X_{min}}{X_{max} - X_{min}} \tag{3}$$

where X_{norm} is the normalized value; X is the original data; X_{max} and X_{min} denote the maximum and minimum values in the range, respectively. After normalization, the mean of all samples for each feature is close to 0 and the standard deviation is 1.

Table 1. Data set

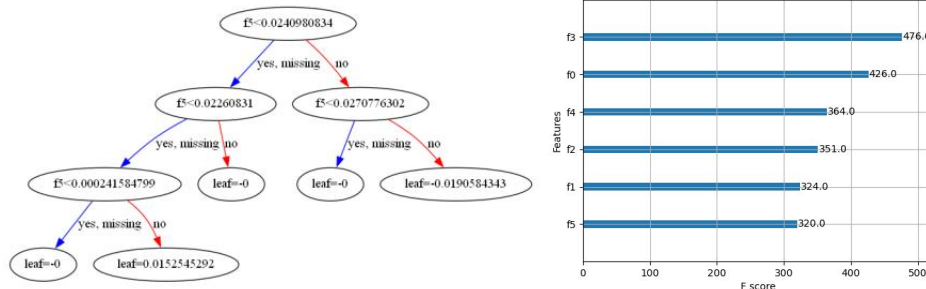
sample	Features						Tags						
	X_1	f_1	d_1	X_2	f_2	d_2	1	R_s	L_s	C_s	R_l	L_l	C_l
1	0.09 5	0.3 37	0.14 4	0.2 45	0.0 77	0.45 9	0.51 1	0.0 88	0.24 2	0.01 3	0.281	0.084	0.029
2	0.20 9	0.8 98	0.74 6	0.5 37	0.5 92	0.38 0	0.77 8	0.0 55	0.08 4	0.04 3	0.202	0.061	0.035
3	0.31 4	0.3 28	0.84 0	0.4 93	0.0 42	0.50 9	0.08 5	0.0 43	0.28 8	0.01 1	0.156	0.118	0.024
4	0.36 7	0.7 96	0.03 7	0.7 27	0.2 66	0.58 3	0.14 0	0.0 23	0.19 8	0.01 8	0.166	0.076	0.033
5	0.07 5	0.9 68	0.61 0	0.3 84	0.0 28	0.55 5	0.42 7	0.0 51	0.24 2	0.01 6	0.248	0.051	0.041
...
1000	0.84 7	0.5 39	0.91 1	0.3 51	0.9 52	0.55 4	0.04 1	0.0 52	0.10 9	0.03 4	0.035	0.139	0.020

3.3 Model construction and performance evaluation

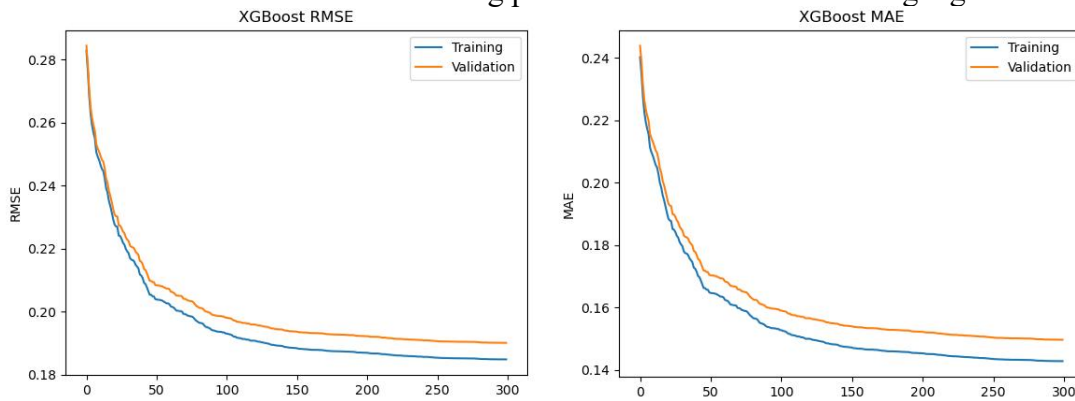
After obtaining the dataset, the model is trained by introducing the machine learning algorithm XGBoost, this study builds the model based on the Python language, the data reading and processing utilizes the Pandas and Numpy modules, and the model is analyzed using the sklearn and Python modules. Overfitting was avoided by incorporating regularization in the design of the model to optimize the model, thus improving the generalization ability of the model [11].

In order to view the model training process, after training the model through Python tool, the training process is visualized and the dendrogram of the decision tree is plotted, which allows observing the splitting conditions of each node and the output values of the leaf nodes in order to understand the decision making process of the model. By plotting a bar graph of feature importance, it helps us to understand which features contribute the most to the performance of the model, as shown in Figure 4.

When using the XGBoost model for prediction, by visualizing the performance during the training process, it is possible to understand the training process and the performance changes of the model, Figure 5 shows the evaluation results of each iteration of the training process, i.e., the root mean squared error and the average absolute error versus the number of iteration rounds.



(a): Training Process Decision Tree Tree Diagram (b): Histogram of importance of characteristics
 Figure 4: Visualization of the decision-making process of the machine learning algorithm XGBoost



(a): Number of Iterations and RMSE (b): Number of Iterations and MAE
 Figure 5. Diagram of the iterative process of evaluating the machine learning algorithm XGBoost

4. Parameter optimization and result analysis

4.1 Optimization Algorithm Fundamentals

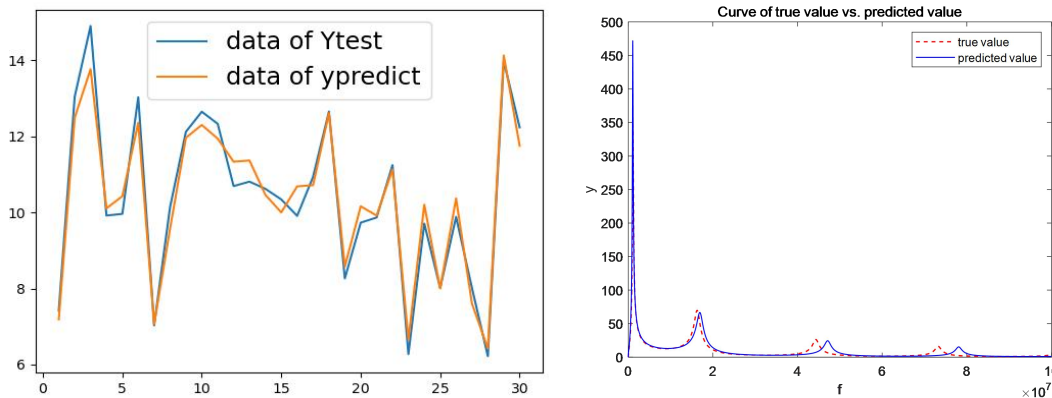
Bayesian optimization is a global optimization algorithm with efficient global search capability, which is capable of constructing a collection function based on the dataset in case the function is unknown, completing the optimal point estimation so as to carry out the prediction of the optimal value, and assessing the model performance using cross-validation. The values of each parameter are shown in Table 2, and the rest of the parameters use the system default parameters:

Table 2. Optimized values of parameters

model parameterization	value
learning_rate	0.1
n_estimators	300
max_depth	5
alpha	10
colsample_bytree	0.3

4.2 Optimization results analysis

After training a good model for prediction, the first choice of measured VFTO waveforms for feature extraction, substituting into the model for training the circuit component parameters, by comparing the measured VFTO waveforms with the predicted simulated VFTO waveforms found that the model in the first two main frequency prediction effect can achieve the expected good results, and the machine learning of the computational cost is low, in the optimization process can withstand the burden of many times to call the numerical value can be efficiently solved the batch processing of the data, with a good effect.



(a):Plot of actual values against predictions (b):comparison of predicted VFTO waveforms

Figure 6: Analysis of optimization results

In order to get the accurate effect of the degree of overlap of the waveforms, Pearson's correlation coefficient as well as cosine similarity is calculated and Table 3 is calculated:

Table 3. XGBoost measures the degree of overlap of predicted waveforms

Assessment of indicators	Pearson correlation coefficient	cosine similarity
value	0.9511	0.9578

The results show that the prediction using XGBoost algorithm is better and can achieve the prediction.

5. Summary

In this paper, the proposed broadband circuit model for VFTO simulation can be used to realize VFTO simulation with pulse generator in the laboratory. Moreover, by establishing an agent model through machine learning, the link between the input circuit component parameters and the output waveform can be established, and Bayesian optimization can be used to achieve the purpose of adjusting the output waveform by adjusting the input circuit component parameters under the premise of the optimized target waveform, thus realizing the simulation of a given VFTO waveform.

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