PREDICTIVE MODELING OF OPERATIONAL STABILITY IN RF NEGATIVE ION SOURCES BASED ON EXPERIMENTAL PARAMETERS

[1]YANG LI, YUQIAN CHEN, [2]YUANZHE ZHAO, YAHONG XIE

[1]East China University of Technology, Nanchang, China
[2]Institute of Plasma Physics, HFIPS, Chinese Academy of Sciences, Hefei, China

Email: 202460076@ecut.edu.cn

1. BACKGROUND

Operational stability of RF negative ion sources serves as a critical foundation for efficient neutral beam injection in tokamak systems [1]. Frequent breakdown phenomena under high-voltage and strong-magnetic-field conditions severely compromise system stability, while traditional empirical prediction methods lack sufficient precision for accurate early warnings, necessitating the development of intelligent predictive models.

2. OBJECTIVES

This study aims to address three fundamental questions: 1. validating the effectiveness of machine learning models for operational stability prediction, 2. comparing performance differences among various algorithms, and 3. identifying critical parameters influencing stability along with their threshold values.

3. METHOD

Utilizing 9,294 experimental datasets from an RF negative ion source test platform, seven key parameters were selected as input features: gas flow (GAS: 0-2000 sccm), RF power (RF: 0-100 kW), bias voltages (BIAS_V, BIAS2_V: 0-50 V), extraction voltage (EXT_V: 0-16 kV), acceleration voltage (ACC_V: 0-200 kV), and magnetic field current (MAG_I: 0~5000 A). Three predictive models were systematically developed: 1. a Gaussian kernel-based RBF-SVM model [2], 2. a Random Forest model integrating optimized decision trees [3], and 3. an SVM-Adaboost hybrid model [4]. Breakdown events (defined as Pulse(s) ≤ 0.5) served as stability failure indicators, with model performance rigorously evaluated through confusion matrices, ROC curves, and AUC metrics [5].

4. KEY RESULTS

The ROC curves of all three models reside above the y=x reference line (Fig. 1), confirming their effectiveness compared to random classification. As demonstrated in Table 1, the Random Forest model achieved optimal stability prediction performance with 98.62% accuracy (AUC: 0.9918), significantly outperforming RBF-SVM (96.13%) and SVM-Adaboost (96.55%). Decision tree node analysis (Fig. 2) revealed a critical threshold for BIAS2_V at 5.27 V, beyond which system stability deteriorates sharply. Parameter importance ranking confirmed BIAS2_V (38.7%), RF power (29.1%), and magnetic field current (17.5%) as the three dominant influencing factors.

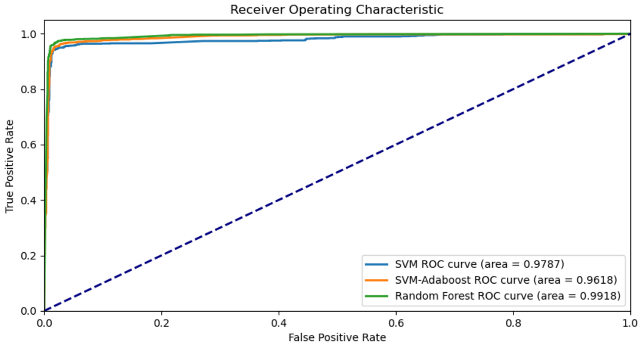

Fig. 1. Testset ROC Curves of Three Models

TABLE 1. PERFORMANCE COMPARISON OF PREDICTION MODELS

Model	Accuracy	Precision	Recall	F1-Score
SVM	0.9613	0.9612	0.9613	0.9612
Random Forest	0.9862	0.9855	0.9870	0.9862
SVM-Adaboost	0.9655	0.9623	0.9661	0.9655

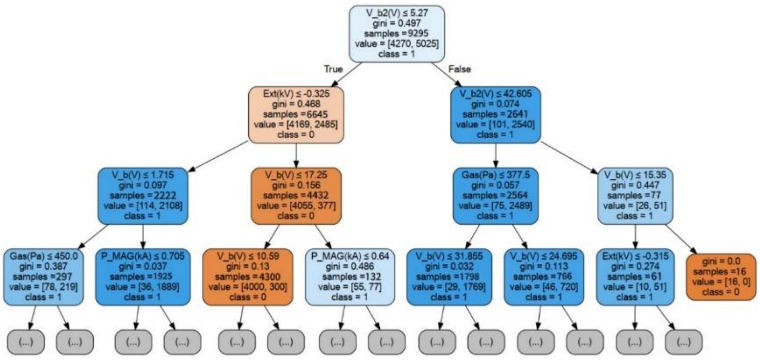

Fig. 2. Decision Tree (Max Depth=3)

5. ANALYSIS AND CONCLUTIONS

The superior performance of Random Forest originates from its dual anti-overfitting mechanisms: Bagging reduces model variance while feature randomness enhances generalization capability [6]. When bias voltage exceeds the threshold, particular attention should be paid to parameter matching relationships to prevent plasma sheath instability, with RF power and magnetic field current interactions further amplifying risks. Decision tree visualization effectively reveals complex nonlinear couplings between parameters.

This study demonstrates that the Random Forest model delivers optimal performance in breakdown prediction across all evaluated metrics (accuracy: 98.62%, AUC: 0.9918). Future studies will focus on optimizing stability evaluation criteria, implementing machine learning for precise power parameter calibration, and developing dynamic prediction models incorporating temporal feature analysis.

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