

# 基于热参数的汽轮发电机组多故障诊断模型

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**摘 要:** 汽轮发电机组故障往往是多因多果, 有些故障单纯依靠频谱很难识别出来。而机组的负荷、相位、转子表面温度的变化也是识别故障的重要信息, 但它们对不同故障的影响有强弱之分。本文对影响汽轮发电机组故障的各征兆群进行了系统分析, 利用子网络技术, 针对不同故障选择不同征兆, 建立了单个诊断网络模型, 有效地解决了征兆作用的冗余和不足, 并进行了实例验证。

**关 键 词:** 振动; 热参数; 故障诊断; 子模型; 神经网络

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息的一部分, 而机组的负荷变化以及工作介质的温度、压力、流量等, 对机器的运行状态有重要的影响, 往往是造成机器异常振动的重要因素。目前, 对振动频谱分析应用十分广泛, 利用温度、压力等慢变参数还不够, 而有时利用相位信号和油温、压力信号可以排除某些故障或精确诊断某些故障<sup>[1]</sup>。如弯曲和不平衡故障引起的振动, 频谱分布近似相同, 只有通过相位才能区分。目前广泛采用的神经网络诊断方法首先需要对认知的标准样本进行训练, 已知征兆作为诊断网络的输入参数。对于多个故障样本的诊

断网络, 一般要求输入节点含义相同, 即不同故障具有相同的征兆域。实际中存在以下缺陷: 同一征兆在不同故障中一视同仁, 削弱了主导征兆对其故障的贡献程度, 其次导致输入征兆的冗余或诊断缺征兆<sup>[2~4]</sup>。

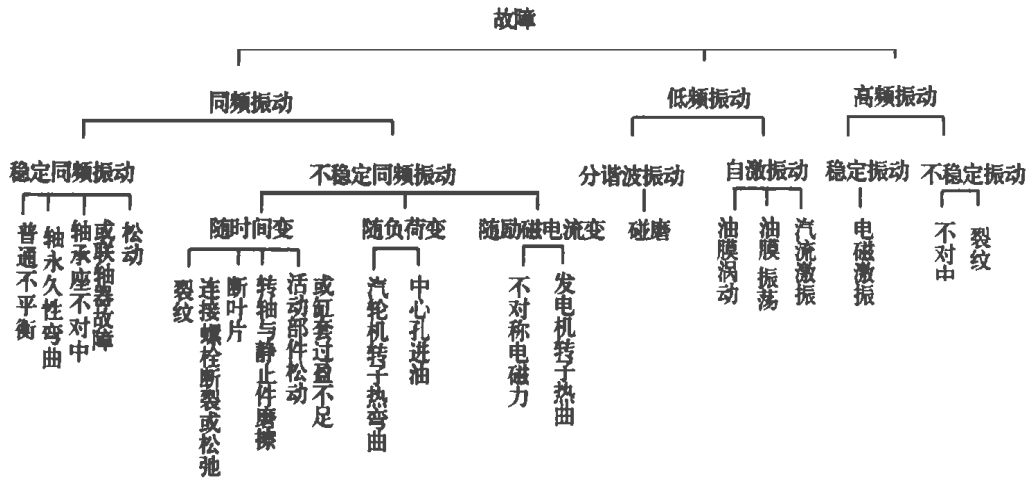


图 1 故障分类

## 1 前言

汽轮发电机组故障是多种故障因素的耦合作用, 机组故障往往是多因多果, 一种故障可能引起多种征兆, 一种征兆可能反映多种故障。单一征兆参数很难全面认识故障, 振动信号从幅值域, 频率域和时间域为故障提供了重要信息, 然而, 它只是故障信

本文基于热参数分析和频谱诊断, 提出子故障诊断模型, 一个子模型负责诊断一个确定故障, 提取的故障征兆即包括特征谱又包含热参数征兆。诊断模型的征兆域可以不同选择, 增加了有用征兆减少了无关征兆, 使故障更易区分。

## 2 故障征兆分析

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故障诊断的过程是根据故障的征兆信息 (如频谱分布、相位变化、振动随热参数的变化趋势等) 去探索故障原因, 找出机组可能存在的缺陷。故障可以通过振动特征谱反映, 也可以体现在随热参数的变化规律上。

除振动频谱 (包括频谱分布及振动谱值变化率), 故障征兆还包括以下方面:

- (1) 历史档案资料 (机组存在的缺陷、曾发生过的故障记录、历次检修记录)
- (2) 机组总体结构、连结方式, 密封形式、轴承型式、测试传感器分布、特性参数和临界转速;
- (3) 振动随运行工况 (时间、有功负荷及励磁电流) 的变化情况;
- (4) 振动发生部位和主要方向;
- (5) 启动过程、停机过程振幅和相位与转速的变化关系;
- (6) 振动随油温变化情况;
- (7) 振动随进汽流量变化情况;
- (8) 振动随油压变化情况;
- (9) 轴承油膜压力变化情况;
- (10) 振动随转子表面温度变化情况;
- (11) 振动是否具有再现性
- (12) 轴心轨迹形状;

上述 12 个征兆域的影响不是等同的, 有些是过程变化参数, 可以进行初步诊断作为分类的依据; 有些参数被赋予可信性因子后可以和频谱一起作为已知输入参数。利用征兆 (1) — (2) 可以获得诊断的背景知识, 如检修过的详细情况, 这和某些故障的有无直接相关, 又如轴承型式和油膜振荡密切相关, 同时还可以保留或删除某些诊断知识, 如能否提取轴心轨迹等。征兆 (3) 反映的是振动的变化规律, 据此可以将故障划分为稳定故障和不稳定故障。利用振动随励磁电流和负荷的变化可以确定故障属于电故障还是和热参数有关的故障, 如果切断电源振动立即减弱, 则可以直接推断出振动的起因与电有关, 如果振动和负荷有关, 则存在一定的热变形和热弯曲。其它征兆在不同故障中存在的形式不同, 取舍视具体故障确定。

利用频谱和上述征兆将常见故障划分为以下几类, 如图 1 所示。有些故障的所属类别不是唯一的。

### 3 诊断网络结构

从以上分析可见, 不同故障的作用征兆不同, 每

个故障对应的输入不完全一样, 因此本文提出了子网络结构构造诊断模型的方法, 每个网络只用于识别一类故障, 可以保证每种故障确定自己的映射空间。

一个网络代表一种故障, 网络输出节点数取 1, 各子网络结构随目标故障确定。结构如图 2 所示, 定义各子网络代表的故障类, 输出节点值代表分类隶属度。为使训练样本有较强的自适应及容错能力, 训练的目标样本为标准样本, 而对于正在修正的新故障样本及含噪声的样本, 则需引入确定性因子  $CF_p$  ( $0 \leq CF_p \leq 1$ )。  $CF_p$  表示第  $p$  个训练样本的确定度, 如第  $p$  个训练样本是标准样本, 则  $CF_p = 1$ , 否则适当调整  $CF_p$  的值, 使  $CF_p < 1$ , 第  $p$  个训练样本的目标输出  $d_p = CF_p$ 。根据实际给定每类故障限定的阈值  $\theta$ , 诊断过程中当某子网络输出大于给定的阈值时, 表示该故障发生。

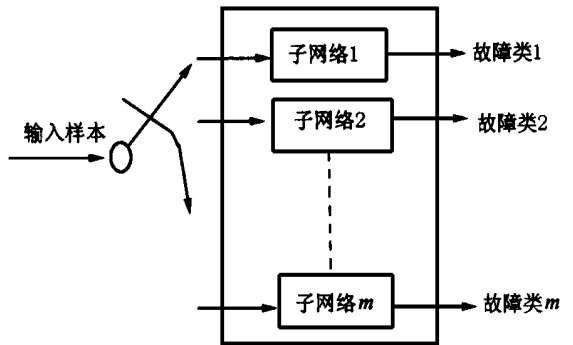


图 2 子网络结构

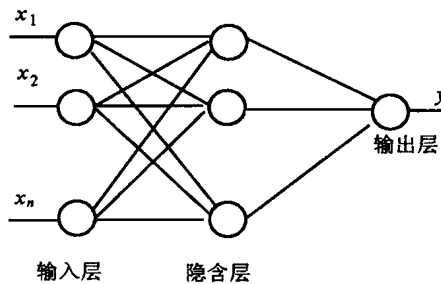


图 3 BP 网络拓扑结构

网络计算采用神经网络的 BP 算法, 图 3 所示为典型三层网络拓扑结构, 子网络  $i$  的输入层作为故障

的征兆层  $[X] = [x_1, x_2, \dots, x_n]$ , 输入的神经元  $\{x_i\}$  代表各征兆元素, 输出层神经元  $[Y]$  为分类隶属度, 网络训练好之后故障知识以权值的形式存储下来。开始训练网络时, 首先给定目标样本, 初选各权值的大小, 经过前向计算和误差反向计算不断修正权值, 直到实际输出和目标输出之间的误差满足精度要求。按照此过程对子网络 1、子网络 2... 子网络  $m$  逐一训练, 每增加一种故障子网络数加 1, 算法详见文

献 5]。

采用子网络诊断模型, 每个网络的输入分别选取, 可以有效避免输入征兆的冗余和不足, 增强网络的识别能力。另外, 当某一网络的参数发生变化或需要增加一种新故障时, 选用子网络结构, 在对原有网络不必重新训练的情况下可以进行网络的学习和扩充。

### 4 故障实例分析

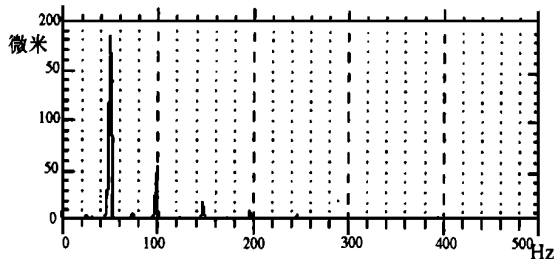


图 4 碰磨频谱图

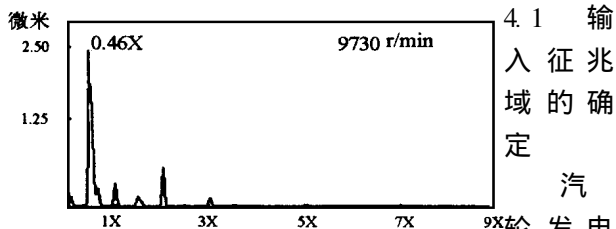


图 5 油膜振荡频谱图

汽轮发电机组产生的低频振动, 除油膜振荡外, 分谐波共振中的碰磨也伴有低频分量, 如图 4、图 5 所示, 图 4 为某机组发生的碰磨信号, 图 5 为实验台采集信号。

表 1 列出了两者的主要差别, 油膜振荡和分谐波共振特征频率不一样外, 还可以通过随转速、负荷的变化规律加以区分。油膜振荡和转速有直接关系, 只有超过二阶临界转速才可能出现。

表 1 油膜振荡和分谐波共振差别列表

| 故障名称  | 振动主频率             | 常伴频率                           | 再现性 | 轴心轨迹形状 | 振动和转速关系      | 振动和负荷关系 |
|-------|-------------------|--------------------------------|-----|--------|--------------|---------|
| 油膜振荡  | $.46f_1 - .48f_1$ | $f_1$                          | 弱   | 不规则    | 规律性强         | 无直接关系   |
| 分谐波共振 | $.5f_1$           | $f_1, 2f_1, 3/2f_1, \text{高频}$ | 碰磨弱 | 不规则    | 低速不明显, 转速高明显 | 规律性强    |

注:  $f_1$  为转速工频

在许多机组上都发生过中心孔进油引起的振动故障, 现象表现为热弯曲。在排除设备本身的缺陷如材质不均、安装误差等因素后, 多次回放信号谱特

征和碰磨信号非常相似, 都伴有分数谐波和高倍频。通过对其它征兆的分析, 比较出两者的主要差别示于表 2。特别是振动随负荷的变化情况以及振动有无再现性是区分这两种故障的关键。图 6 是某机组中心孔进油振动变化趋势图。

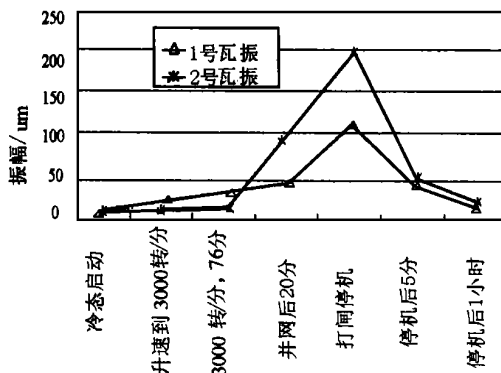


图 6 中心孔进油振动变化趋势

以上举例说明在相似故障之间只能借助某些过程参数才可区分, 且识别不同故障的关键征兆不同。

表 2 碰磨和中心孔进油振动差别列表

| 故障名称  | 频率分量                        | 高频分量        | 负荷关系  | 振动再现性 |
|-------|-----------------------------|-------------|-------|-------|
| 碰磨    | $12f_1, 3/2f_1, f_1, 2f_1$  | 高频 $6-8f_1$ | 关系弱   | 弱     |
| 中心孔进油 | $1/2f_1, 3/2f_1, f_1, 2f_1$ | 无           | 强线性关系 | 强     |

### 4.2 诊断实例

对上述所举故障建立诊断网络模型, 构造三个小网络, 分别代表油膜振荡、碰磨、中心孔进油。每个模型的输入列于表 3, 表中数据是经过多次样本试验得到。

表 3 诊断结果

| 故障名称  | $f_1$ | $.4f_1$ | $1/2f_1$ | $2f_1$ | $3f_1$ | $>3f_1$ | 随油温变 | 随负荷变 | 随转速变 | 随时间变 | 削波性强 | 再现性变化 | 相位 |
|-------|-------|---------|----------|--------|--------|---------|------|------|------|------|------|-------|----|
| 油膜振荡  | 0     | 1       | 0        | 0      | 0      | 0       | 1    | 0    | 1    | 0.6  | 0    | 0.2   | 1  |
| 碰磨    | 0.3   | 0.05    | 0.2      | 0.2    | 0.05   | 0.2     | 0.3  | 0.6  | 0.7  | 0.7  | 0.8  | 0.3   | 1  |
| 中心孔进油 | 0.7   | 0       | 0.05     | 0.2    | 0.05   | 0       | 0    | 1    | 0.7  | 1.0  | 0    | 1     | 1  |

注: 表中数字代表该征兆的可信性因子

分别训练三个子网络, 学习精度为 0.01, 网络收敛之后, 利用实际样本进行诊断测试。文中所举的三种故障信号分别送入三个子网络, 诊断结果见表 4。

表 4 诊断结果

| 样本     | 子网络 1 | 子网络 2 | 子网络 3 |
|--------|-------|-------|-------|
| 油膜振荡 1 | 0.991 | 0.126 | 0.090 |
| 油膜振荡 2 | 0.926 | 0.191 | 0.218 |
| 碰磨 1   | 0.157 | 0.894 | 0.201 |
| 碰磨 2   | 0.117 | 0.933 | 0.212 |
| 中心孔进油  | 0.093 | 0.281 | 0.876 |

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## 4.2 内模控制系统的仿真研究

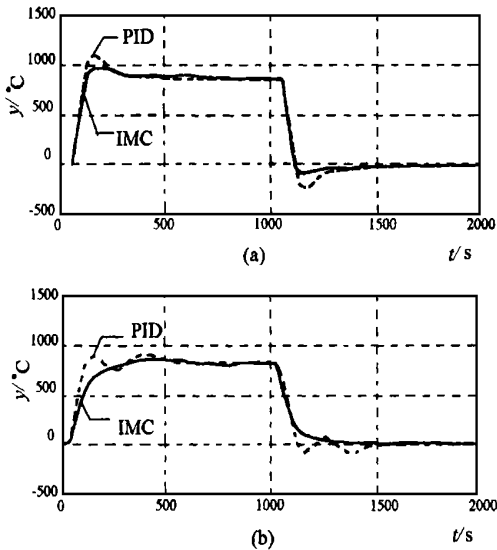


图 3 仿真曲线

用训练好的图 2 所示的 Elman 网络代替图 1 中的  $M_d^{-1}$  环节。当网络训练好后, 控制系统的可调参数为线性滤波器  $F(z) = \frac{1 - \alpha_f}{1 - \alpha_f z^{-1}}$  中的参数  $\alpha_f$ , 可根据对跟踪性能和抗扰动能力的要求进行选取, 在此取  $\alpha_f = 0.3$ , 利用 MATLAB 中的 Simulink 工具箱进行仿真, 并与常规 PID 控制系统 (其参数根据 Z-N 法进行整定) 进行比较。当设定值取为 0 秒和 1000 秒的正向、反向阶跃信号 (幅值为  $850^\circ\text{C}$ ) 时, 响应曲线如图 3 所示。

当  $G_0(s)$  取 80% 负荷的参数时的曲线如图 3(a), 可见, 当不存在模型误差时, IMC 的控制效果与

PID 控制的差别不很明显; 当  $G_0(s)$  取 100% 负荷的参数时的曲线如图 3(b), 其中 PID 调节器参数保持不变, 可见, 当存在模型误差时, IMC 的控制效果要明显优于 PID 控制系统, 能够满足实际运行要求。由于此时的模型误差是由负荷变动引起, 因此, 图 3(b) 也可以看作是负荷扰动下的响应, 这也就说明与 PID 控制系统相比, 内模控制系统具有很强的鲁棒性和抗扰动能力。

## 5 结论

本文采用改进的 Elman 网络辨识对象逆模型, 将其用于内模控制系统中, 使得基于神经网络的内模控制更好地适用于高阶对象。对循环流化床中床层温度对象的仿真研究表明, 基于改进的 Elman 网络的内模控制系统具有优良的控制性能。

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测试结果表明; 建立的诊断子网络可以有效地区分上述几种故障, 并且和常规的诊断网络进行了比较, 区分度明显增强。

## 5 结束语

本文从全面认识故障的角度出发, 提出了基于热参数的汽轮发电机组故障诊断模型, 单利用频谱分析不能得到诊断结论时, 借助热参数可以区分相似故障。文中采用了子网络技术, 在建立不同故障的诊断模型时输入参数可以单独选择, 有效地解决了输入参数作用的冗余和不足, 可以突出每类故障主导征兆的贡献。今后, 应加强故障机理特征提取

的研究, 使诊断知识日臻完善。

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(渠 源 编辑)

sion-based speed regulation devices. In connection with practical uses the performance of these devices are also compared with that of other types of speed-regulation ones. **Key words:** frequency conversion-based speed regulation, rectification, inversion, constant torque

状态监测与诊断用燃气轮机热力模型的构造方法 = A Method for the Construction of a Thermodynamic Model for Gas Turbine Engine Condition Monitoring and Diagnosis [刊, 汉] / XIE Zhi-wu, ZHANG Ren-xing (Naval Engineering University, Wuhan, Hubei, China, Post Code: 430033), WANG Yong-hong (Shanghai Jiaotong University, Shanghai, China, Post Code: 200030) // Journal of Engineering for Thermal Energy & Power. — 2000, 15(4). — 410 ~ 412

The authors have proposed a new method of model construction for the prediction of gas turbine off-design performance. Instead of relying on an engine's published design point data the proposed method uses calibrated acceptance test data to serve as the basis for engine performance evaluation and prediction. The deviation in performance of a specific engine from the model's average performance has been taken into account in the model with no need for further rectification. The off-design performance of the single-shaft gas turbine of a power station has been evaluated by using the present method. The calculated results are in fairly good agreement with the published data, thus testifying to the validity of the method. The latter is particularly suited for use in gas turbine condition monitoring and diagnosis. **Key words:** gas turbine, computer-based simulation, thermodynamic model, condition monitoring and diagnosis

舰船用热工参数智能数字检测仪的设计和应用 = Design and Application of Intelligent and Digital Devices for the Measurement and Detection of Thermodynamic Parameters of Naval Propulsion Plants [刊, 汉] / LUO Kang-ming (Harbin No. 703 Research Institute, Harbin, China, 150036) // Journal of Engineering for Thermal Energy & Power. — 2000, 15(4). — 413 ~ 416

With the successful development of Model SZW-01 intelligent and digital display devices it is now possible to realize the automatic measurement and detection on-site of the thermodynamic parameters of a naval main propulsion plant. Moreover, the display of all these parameters can be concentrated on a few command posts with alarm functions also provided. Described in this paper are the design of the computer system hardware and software of the above-cited intelligent and digital display device, its tests as well as its installation on board a naval vessel for routine operation. **Key words:** scale transformation, digital zero-setting, full automatic calibration, failure diagnosis

一种基于 PLC 的火电厂微机监控系统及其数据通信的实现 = Programmable Logic Controller-based Microcomputer Monitoring System for a Thermal Power Plant and Realization of Its Data Communication [刊, 汉] / XIAO Da-chu, GE Peng, LIAO Qun (Thermal Power Engineering Department, Wuhan University of Water Resources and Electrical Power, Wuhan, Hubei, China, Post Code: 430072) // Journal of Engineering for Thermal Energy & Power. — 2000, 15(4). — 417 ~ 419

With the data acquisition system (DAS) modification project of Hebi Thermal Power Plant being taken as an example and based on DDE and Net DDE mechanism under Windows environment the authors expound a monitoring system structure, hardware and software configuration, its performance and a realization of network data communication. All the above has provided a well thought-out approach for the development of a microcomputer-based monitoring system for use in thermal power plants. **Key words:** thermal power plant, microcomputer-based monitoring system, dynamic data exchange, data communication

基于热参数的汽轮发电机组多故障诊断模型 = Multiple-failure Diagnosis Model of Turbogenerators Based on Thermodynamic Parameters [刊, 汉] / GE Zhi-hua, SONG Zhi-ping, LI Ru-xiang, TIAN Song-feng (North China Electrical Power University, Baoding, Hebei, China, Post Code: 071003) // Journal of Engineering for Thermal Energy

&Power . — 2000, 15(4). — 420 ~ 422, 431

Turbogenerator failures and malfunctions are often caused by a multitude of factors. Some of the failures can hardly be identified and detected by solely relying on frequency spectrum features. Moreover, the variation in the turbogenerator load, phase and the rotor surface temperature can also serve as vital information for identifying and detecting its failures and malfunctions, though their influence on the latter may be a strong or weak one. A systematic analysis is conducted of the effect of various symptom groups on the emergence of turbogenerator failures and faults. By the selection of different symptoms for different failures a single diagnosis network model has been set up based on the use of a sub-network technology. This has effectively resolved the problem of symptom function redundancy and insufficiency. An experimental verification of the model was also fulfilled by a series of illustrative examples. **Key words:** vibration, thermodynamic parameter, failure diagnosis, sub-model, neural network

**基于神经网络的燃气轮机动态过程仿真 = Simulation of a Gas Turbine Dynamic Process on the Basis of a Neural Network** [刊, 汉] / ZENG Jin, REN Qing-sheng, WENG Shi-lie, SUN Wei-rong (Applied Mathematics Department, Shanghai Jiaotong University, Shanghai, China, Post Code: 230030) // Journal of Engineering for Thermal Energy &Power . — 2000, 15(4). — 423 ~ 425

The digital simulation of gas turbines features a variety of advantages such as a high performance-to-cost ratio and a high simulation accuracy, etc. However, the traditional simulation modeling method often suffers from an inability to simultaneously meet the requirements of gas turbine simulation precision and real-time function. In view of this, the authors have conducted a huge amount of exploratory work concerning the construction of neural networks with a large sample space as well as an intensive study on the network learning acceleration method. As a result, they have eventually succeeded in introducing the neural network technology into the simulation of gas turbines, resulting in the construction of a new simulation model. This has led not only to a higher simulation precision but also to a retaining of the system original smoothness. Furthermore, it has also satisfied the system real-time function. **Key words:** gas turbine, simulation, neural network, BP algorithm

**基于模糊数学和 RBF 神经网络的事事故预测 = Failure Prediction Based on Both Fuzzy Mathematics and a Radial Basis Function (RBF) Neural Network** [刊, 汉] / BI Mei-hua, XIAO Li-chuan, XUE Guo-xin (Computer Department, Jiangsu Petrochemical Institute, Changzhou, Jiangsu, China Post Code: 213016) // Journal of Engineering for Thermal Energy &Power . — 2000, 15(4). — 426 ~ 428

It is of crucial importance to have the ability to predict incipient and potential failures of a power plant or chemical engineering process unit during its operation by tracing the development trend of relevant variables. A comprehensive research has been performed in this regard, and a series of promising results have been attained, especially regarding the application of intelligent software for coping with the relevant issues. However, all the traditional methods are mostly based on the analysis of failure modes. In this paper proposed is a fuzzy mathematics-aided method with the use of RBF neural network method to identify failure symptoms. Satisfactory results have been obtained when the proposed method was used to predict the failure of a coal-fired boiler. **Key words:** failure prediction, fuzzy mathematics, radial basis function (RBF) neural network, coal-fired boiler

**基于改进的 Elman 网络的内模控制及其应用 = Internal Model Control Based on an Improved Elman Network and its Applications** [刊, 汉] / MA Bao-ping, XU Zhi-gao (Power Engineering Department, Southeastern University, Nanjing, Jiangsu, China, Post Code: 210086) // Journal of Engineering for Thermal Energy &Power . — 2000, 15(4). — 429 ~ 431

To achieve a better use of the neural network-based internal model control on higher order objects, the present paper proposes an internal model control system based on an improved Elman network. Furthermore, with the temperature of a bed