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非线性时间序列的 RBF 神经网络预测方法及其应用

张传斌, 王学孝, 邓正隆
(哈尔滨工业大学 航天学院, 黑龙江 哈尔滨　150001)

摘　要: 将一种基于自动增加隐节点数目训练算法的径向基函数(RBF)神经网络用于非线性时间序列预测。这种方法成功地解决了 BP 网络的局部极小、隐节点数目的选择和过拟合问题, 并用于热电厂热负荷预测。预测结果表明, 用本方法进行热负荷预测得到了十分满意的结果。

关　键　词: 非线性时间序列; 预测; RBF 神经网络; 热负荷

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1　前言

随着人工神经网络技术的发展, 神经网络被广泛应用于各种领域。用神经网络方法对非线性时间序列进行预测成为一种重要的非线性预测方法。目前神经网络非线性预测主要采用 BP 网络。由于 BP 网络采用反向传播学习算法, 不可避免地存在局部极小问题; 而且隐层节点数目的选择只能靠试凑; 导至网络的泛化能力较差。

本文采用基于增长型结构学习算法的 RBF 神经网络用于热电厂热负荷预测, 并将预测结果与文献[2]中采用 BP 网络的预测结果加以比较。

2　RBF 神经网络及学习算法

2.1　RBF 神经网络结构

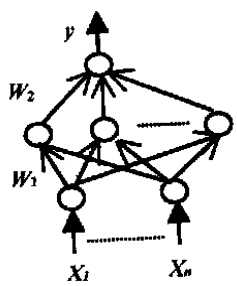

图 1　RBF 神经网络结构图

径向基函数: $G(r) = \exp(-(r/\beta)^2)$

网络的输出:

$$y = W_0 + \sum_{j=1}^{m} W_j F_j(\|X - C_i\|)$$

其中: m 为隐节点数, X 为输入向量, W_j 为权值, C_i 为第 i 个隐节点的 RBF 中心。

2.2　RBF 神经网络的逼近能力

Hornik 等人于1989年证明了如下的神经网络逼近定理[3]:

对于任意给定的函数 $f(x_1, x_2, \cdots, x_n)$ 和误差精度 $\varepsilon > 0$, 总存在一个三层前向网络, 其隐层神经元的作用函数为 $\sigma(x)$, 输入层与输出层为线性神经元。神经网络总输入输出之间的关系: $Y = f(x_1, x_2, \cdots, x_n)$ 能以规定的精度逼近给定的函数 $f(x_1, x_2, \cdots, x_n)$。

由于 RBF 神经网络也是一种多层前向网络, 且满足逼近定理, 所以单隐层的 RBF 神经网络能以任意精度逼近定义在 R^n 上的任意非线性函数。

2.3　神经网络增长型结构学习算法[4]

增长型结构学习算法是提高网络泛化能力的有效办法。Cascade－Correlation 学习算法能实现任意输入－输出关系, 是目前最为成功的增长算法, 它是通过使网络输出的残差与候选隐层神经元之间的相关系数最大来逐一增加隐层神经元实现增长学习的。这种算法学习速度非常快且能自动构造近优网络, 本文采用此算法进行网络训练。

算法的学习过程分为两个阶段, 输出神经元的学习和隐层神经元的学习。步骤如下:

首先构造两层神经网络, 除一个神经元外, 其余连接的权为零。

其次, 设计输出神经元的阈值, 尽可能使输出误差最小。

最后插入第一隐层, 每次增加一个神经元。这一步的训练包括两个阶段:

第一阶段－增加一个隐层神经元, 仅将其与输入神经元相连, 而不与输出神经元相连。调整这些连接权使此隐层神经元的输出与网络输出误差的相关系数最大。

第二阶段－将新增加的隐层神经元的输出与所有输出层神经元相连, 并训练输出层的连接权, 按 δ规则进行使误差最小。

网络误差达到某一稳定值后, 如果还没有达到给定的指标或指定的训练次数, 算法会产生新的隐

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作者简介: 张传斌(1972－), 男, 山东巨野人, 哈尔滨工业大学博士研究生。

层神经元。这个过程被重复直至达到误差精度或最大步数为止。

在实际使用中，一般采用单隐层。若需增加隐层，则重复上面的训练过程即可。

2.4 RBF 神经网络的结构设计

输入层与输出层的神经元数目是实际问题本身决定的，设计网络的过程中应尽量减小网络的规模。由神经网络逼近定理可知：选择单隐层即可。隐层神经元数目的选择可由增长型结构学习算法自动构造。

3 非线性时间序列的 RBF 神经网络预测模型

非线性时间序列预测一般是基于 NAR 模型：

$$x_t = f(x_{t-1}, x_{t-2}, \cdots, x_{t-p}) + e_t \quad (1)$$

其中：$E(e_t \mid x_{t-1}, \cdots) = 0$，且 e_t 存在有限方差 σ^2。

则最小方差预测为：

$$\hat{x_t} = f(x_{t-1}, \cdots, x_{t-p}) \quad (2)$$

用 RBF 神经网络逼近函数 f 即得一步预测：

$$\hat{x_t} = NN\Phi(x_{t-1}, \cdots, x_{t-p}) \quad (3)$$

同理可得 d 步预测：

$$\hat{x_{t+d-1}} = NN\Phi(x_{t-1}, \cdots, x_{t-p}) \quad (4)$$

以模型的一步预测误差来确定模型阶次 p。

4 应用例子

将基于增长型结构学习算法的 RBF 神经网络用于热电厂热负荷预测，采用文献[1] 中给出的 1987 ~ 1993 年的热负荷数据。用 1987 ~ 1991 年的数据作为训练样本，对 1992 ~ 1993 年的热负荷进行预测，并将预测结果与文献[2] 中的结果相比较。

神经网络的输入节点数就是 NAR 模型的阶数 P，预测结果与 P 及隐节点数有关。实际应用中的原则是：在阶次 P 尽量低的条件下，获得高精度的预测结果。

下面给出 $P = 2 \sim 8$ 时的最大预测方差及隐节点数目的选择（如表 1）。

其中：E_T 为训练误差，N_H 为隐节点数目，σ^2 为最大预测方差。

从表中可以看出：预测结果与 P 不是成正比例变化，预测的精度并不随着预测模型的阶次 P 的增加而提高，而是存在最佳的 P 使预测误差最小。

当 $P = 2$ 时，采用本文的方法训练误差选为 $E_T = 1e-3$，隐神经元数目为 3 个，最大预测方差为 1.9 e－3，而文献[2] 中采用 BP 网络，$P = 8$ 时，隐神经元数目为 8 个，最大预测方差为 2.6 e－3。图 2、图 3 是 $P = 2$ 时采用 RBF 神经网络训练和预测的结果。

表 1

P	E_T	N_H	σ^2
2	1e－3	3	1.9e－3
	1e－4	6	3.2e－4
3	1e－3	6	3.5e－3
	1e－4	10	7.6e－4
4	1e－3	6	5.2e－4
	1e－4	14	4.3e－4
5	1e－3	11	1.6e－3
	1e－4	15	1.5e－4
6	1e－3	15	3.6e－3
	1e－4	21	2.4e－3
7	1e－3	16	6.5e－3
	1e－4	28	2.6e－3
8	1e－3	17	4.4e－3
	1e－4	29	2.1e－3

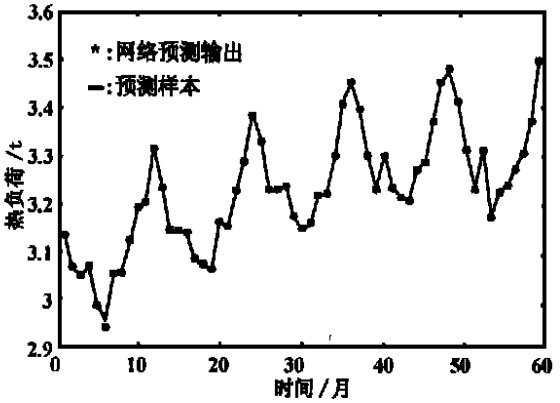

图 2 $P = 2$ 时网络训练结果

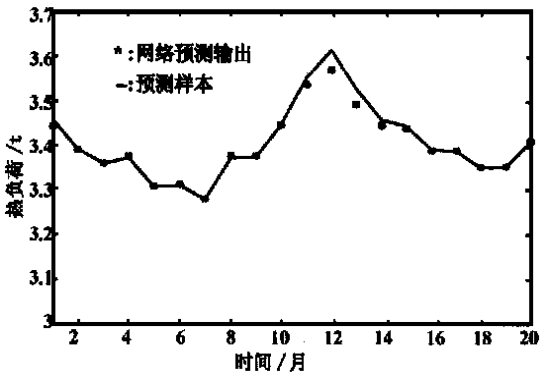

图 3 $P = 2$ 时网络预测结果

从网络结构的复杂性和预测精度来看，$P = 4$ 时是最优的，与 $P = 2$ 相比当训练误差均选为 0.001 时，$P = 4$ 时的隐节点数为 6 个，比 $P = 2$ 时多 3 个，

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$$X_2 = \frac{1}{478.5\times 1.94\times 10^{-3}}\times(e^{-3.18+1.94\times 10^{-3}\times 936} - e^{-3.18+1.94\times 10^{-3}\times 600}) = 0.1318\ (\mathrm{m})$$

选用厚度为 0.13 m。

校核 t_2:

$$t_2 = \frac{1}{1.94\times 10^{-3}}[\ln(e^{-3.18+1.94\times 10^{-3}\times 936} - 478.5\times 1.94\times 10^{-3}\times 0.13) + 3.18] = 607\ (℃)$$

符合要求。

根据 $\rho = 160\ \mathrm{kg/m^3}$, 查得 $A = -3.17$ $B = 1.63\times 10^{-3}$

$$X_3 = \frac{1}{478.5\times 1.63\times 10^{-3}}\times(e^{-3.17+1.63\times 10^{-3}\times 607} - e^{-3.17+1.63\times 10^{-3}\times 60}) = 0.085\ (\mathrm{m})$$

选用厚度为 0.085 m, t_3 不需校核。

5 高温烟箱门与炉体间的密封

由于锅炉炉膛呈微正压(一般为 100 ~ 200 Pa), 所以密封压力不高, 但是温度较高。在这种情况下用耐火纤维毡做密封材料比石棉绳要好。但耐火纤维毡耐压能力差, 一般压缩比控制在 3:1 范围内。用耐火纤维毡密封可不必象石棉绳那样加密封槽, 用平面压紧即可。密封材料厚度 10 ~ 20 mm, 宽度为 30 ~ 50 mm。

6 使用效果

抗风蚀耐火纤维复合炉衬及密封结构已经过一个采暖期的考验, 证明这种材料保温性能好, 实际运行中外表面温度仅 40 ℃, 炉门无跑烟漏气现象。采暖期过后打开炉门观察, 炉衬完好无损, 证明材料选择和结构设计是正确的。

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但预测精度提高了一个数量级。图 4、图 5 分别是 $P = 4$ 时的训练和预测的结果。

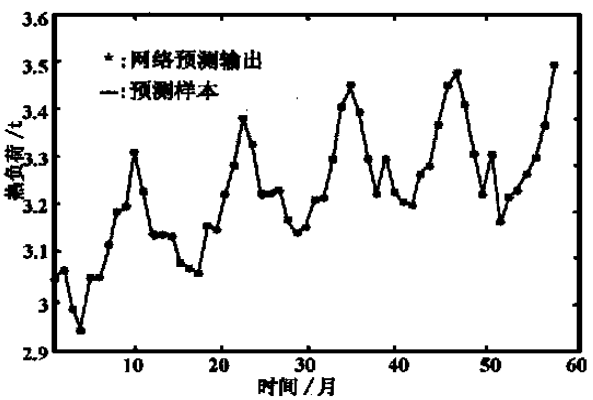

图 4 $P = 4$ 时网络训练结果

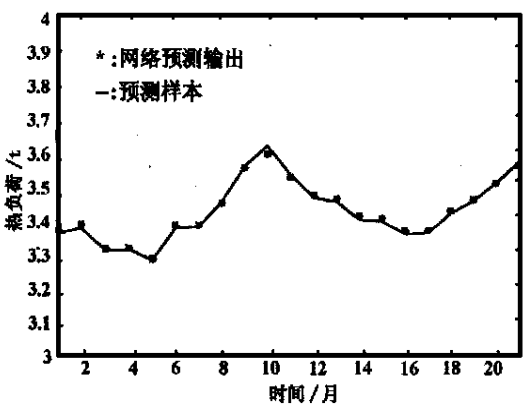

图 5 $P = 4$ 时网络预测结果

从上述 $P = 2$ 和 $P = 4$ 训练和预测的结果可以看出本文中的方法网络结构比文献[2] 的结构简单, 预测精度高。

5 结论

(1) 采用基于增长型结构学习算法的 RBF 神经网络, 具有结构简单、预测精度高的特点。用于热电厂热负荷预测获得了十分满意的结果。

(2) 由于 RBF 神经网络不存在局部极小问题, 增长型结构学习算法自动构造近优的网络, 从根本上解决了过拟合问题, 提高了网络的泛化能力。

(3) 应用例子进一步说明了本文中的方法比文献[2] 中的方法更简单、合理、具有普遍性。

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cerning Faults and Malfunctions of a Dual-channel Steam Condenser on the Basis of a Simulation Model [刊, 汉] / MA Liang-yu, WANG Bing-shu, GAO Jian-qiang, MA Yong-guang, TONG Zhen-sheng (Research Institute of Simulation and Control Technology under the North China Electric Power University, Baoding, China, Post Code: 071003) // Journal of Engineering for Thermal Energy & Power. —2001, 16(3). —298 ~ 302

In performing a fault diagnosis of thermal equipment it is usually difficult to create accurately and adequately a fault diagnosis knowledge base for the concerned equipment. This comes about because of two reasons: 1. Complexity of equipment, system and faults themselves; 2. Improper method of extracting the sample knowledge of frequently encountered faults. To cope with this problem, a new method for extracting fault sample knowledge of thermal equipment has been proposed by taking advantage of the technical edge enjoyed by simulation technology in the modeling of power station equipment and systems. By the use of the proposed method and through the creation of a dynamic mathematical model for a double-channel condenser a detailed simulation test of the equipment faults was conducted. On the basis of summing up on-site operating experience and performing a related theoretical analysis a typical fault knowledge base has been finally consummated for the dual-channel steam condenser. **Key words**: dual-channel steam condenser, failure and fault, sample knowledge extraction, simulation model

机械驱动用单轴燃气轮机动态模型研究＝**Dynamic Model Research of a Single-shaft Gas Turbine in Mechanical Drive Applications** [刊, 汉] / WEI Si-liang, LIU Shang-ming, NI Wei-dou (Tsinghua University, Beijing, China, Post Code: 100084) // Journal of Engineering for Thermal Energy & Power. —2001, 16(3). —303 ~ 307

With the continuous improvement in gas turbine performance its scope of applications is widening dramatically. Apart from its use in power generating units and combined cycle power plants there emerged ever more cases of its application as a variable-speed mechanical drive unit. Presented in this paper is a model of single-shaft gas turbine in mechanical drive service including its control system. The model has been simplified in light of specific conditions. Under a Matlab/Simulink environment a simulation was conducted of the process of load and speed increase-decrease as well as load rejection. The results of simulation agree quite well with actual physical processes. Hence, the proposed model can be employed for the study of a single-shaft gas turbine and its control system. **Key words**: gas turbine, simulation, dynamic model.

电站锅炉燃烧系统仿真模型的建立＝**The Building of a Simulation Model for a Utility Boiler Combustion System** [刊, 汉] / CHEN Li-jia, WANG Zi-cai, ZHU Qun-yi (Harbin Institute of Technology, Harbin, China, Post Code: 150001) // Journal of Engineering for Thermal Energy & Power. —2001, 16(3). —308 ~ 310

In a real-time simulation system for a utility boiler it is common practice to adopt a zero-dimensional model for building a model of combustion system. This is understandable, because the aim of a simulation consists in simulating the dynamic behavior of an actual system in its full range of operation. However, the zero-dimensional model has oversimplified the complicated process of a combustion system. In view of this, when the operating load of a system fluctuates over a relatively large range, there will emerge a very large error or difference between a zero-dimensional model and an actual system. Under proper hypothetical conditions the authors have set up a one-dimensional model capable of reflecting the interior conditions of a combustion system and performed a simulation of the model. The results of simulation indicate that the recommended model features a very high precision. It has already been employed on the simulation of a 210 MW thermal power plant with its suitability for the intended purpose being verified. **Key words**: utility boiler, combustion system simulation, combustion model, real-time simulation

非线性时间序列的 RBF 神经网络预测方法及其应用＝**A Method for Predicting Nonlinear Time Series Using RBF (Radial Base Function) Neural Network and Its Application** [刊, 汉] / ZHANG Chuan-bin, DENG Zheng-long (Astronautics Institute under the Harbin Institute of Technology, Harbin, China, Post Code: 150001) // Journal of Engineering for Thermal Energy & Power. —2001, 16(3). —311 ~ 312, 342

An innovative method involving the use of RBF (radial base function) neural network based on a training algorithm of au-

tomatic increase in hidden nodes has been employed to predict nonlinear time series. The proposed method allows to successfully tackle the problem of selecting local minimal hidden node number and excessive fitting in BP networks. It has been applied to predict the thermal loads of a thermal power plant. The results of prediction indicate that very satisfactory results have been achieved in forecasting the thermal loads of power plants. **Key words**: nonlinear time series, prediction, RBF (radial base function) neural network, thermal load

面向对象方法与转子故障监测诊断系统的开发=**Description of an Object-orientated Methodology and Development of a Rotor Failure Monitoring/diagnosis System** [刊, 汉] / ZHANG Heng-liang, ZHANG Qin, CHEN Ru-qing (Power Engineering Department, Wuhan University of Water Resources and Electric Power, Wuhan, China, Post Code: 430072) // Journal of Engineering for Thermal Energy & Power. —2001, 16(3). —313 ~ 315

In recent years there existed some problems of poor self-stability and certain difficulties involved in the maintenance and upgrading of rotor-failure monitoring and diagnostic systems during their use in industrial fields. The proposed object-orientated method represents a good software development approach, which has been assessed as a major method for use in a software development process. The present paper gives a brief description of the method, highlighting how to use such a method to develop a rotor failure monitoring and diagnostic system. **Key words**: monitoring and diagnostic system, object-orientated methodology, rotor failure monitoring

流体流动的输出功率与功率耗散的协调优化=**Optimized Coordination of Fluid-flow Output-Power and Power Dissipation** [刊, 汉] / YAN Ning-rong (Department of Mechanical Engineering, Lujiang University, Xiamen, Fujian Province, China, Post Code: 361005) // Journal of Engineering for Thermal Energy & Power. —2001, 16(3). —316 ~ 318

Ecological optimization criteria have been popularized for use in the analysis of the optimized performance of a fluid-flow work-doing unit. Some new performance parameters were derived and discussed in a meaningful way. Expounded further was the major significance of the ecological optimization criteria. The conclusions obtained may serve as new theoretical guidelines for the optimized design and selection of optimized working conditions for fluid-flow work-doing units. **Key words**: fluid-flow work-doing device, ecological optimization criteria, optimized performance

循环流化床烟气脱硫床料的质量平衡和化学成份的变化=**Mass Equilibrium of Gas Desulfurization Bed Materials in a Circulating Fluidized Bed and the Variation of Chemical Composition** [刊, 汉] / FAN Bao-guo, QI Hai-ying, YOU Chang-fu, et al (National Key Lab of Coal Clean Combustion under the Tsinghua University, Beijing, China, Post Code: 100084) // Journal of Engineering for Thermal Energy & Power. —2001, 16(3). —319 ~ 321

A theoretical analysis was conducted of the variation of bed materials mass and chemical composition in the desulfurization process in a circulating fluidized bed. It has been found that with the circulation ratio selected at 5-50 and the effectiveness of a separator attaining 83%-98% it is possible to maintain a mass equilibrium in the bed. In case a change of operating parameters gives rise to a change of mass of in-bed materials, it is possible through a quantitative change of bed materials leaving the bed to attain equilibrium very rapidly. By contrast, the dynamic state of chemical composition is unbalanced. Its transition process has been found to be dependent on bed material quantity in the bed, production rate of reaction products and the variation range of related parameters, etc. **Key words**: circulating fluidized bed, gas desulfurization, bed materials mass and chemical composition

利用双节流元件测量两相流干度=**The Measurement of Two-phase Flow Dryness by the Use of a Dual-throttle Element** [刊, 汉] / YE Qiang, CHEN Ting-kuan, LUO Yu-shan (National Key Lab of Multi-phase Flows under the Xi'an Jiaotong University, Xi'an, China, Post Code: 710049) // Journal of Engineering for Thermal Energy & Power. —2001, 16(3). —322 ~ 324

Based on a model of classical uniform-phase flow and divided-phase flow the authors have deduced a formula for the direct measurement of dual-phase flow under an ideal condition. The applicable scope of usage of the formula is analyzed. An experimental device has been designed, which incorporates a horizontal orifice plate and a vertical descending Venturi