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传感器故障检测的 Powell 神经网络方法

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摘　要: 大型热力控制系统必须能够检测传感器故障, 并采取相应的措施, 保证控制过程的顺利进行。提出了一种基于 Powell 神经网络的故障检测新方法, 为系统中每一个传感器构造一个神经网络观测器, 首先离线训练神经网络观测器, 然后进行故障检测并同时在线训练, 利用神经网络估计输出代替故障传感器输出, 保证系统的稳定。神经网络的训练采用 Powell 方法, 该训练方法的收敛速度快、过程稳定。本方法具有在线学习、诊断多个传感器故障等优点。锅炉的实际试验结果表明, 此方法行之有效。

关　键　词: 神经网络; 故障检测; 故障诊断; 传感器

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1　前言

大型热力系统的控制系统需具备故障容错能力, 以确保当系统中某些部件(如传感器等)损坏时, 整个系统仍能正常工作。控制系统中传感器用于监测温度、压力、压差等信号, 以保证系统正常运行, 传感器的故障可能会导致系统运行性能下降甚至瘫痪。作为测量控制系统中诸参量的关键部件, 传感器输出信号的质量直接关系到整个系统的性能好坏。如果传感器发生故障, 无论是硬故障还是软故障, 都会影响系统的正常运行。事实上, 传感器正是控制系统中比较容易损坏的部件, 因此控制系统应具备对传感器故障的容错能力。首先控制系统需诊断传感器是否发生故障, 即对传感器输出进行校验, 如果检测到传感器发生了故障, 则报警通知操作人员, 并调用备份传感器, 或重构控制律以确保整个控制过程的顺利进行。

目前采用较多的传感器故障诊断方法是分析冗余法[1], 以线性控制理论为理论基础, 需求建立系统的精确数学模型, 只适于线性和低阶系统。而人工神经网络不需要知道系统的数学模型, 只通过样本的学习来掌握数据之间的关系, 因而可以用于传感器故障诊断和信号恢复[2]。

由于实际的热力系统多是有时滞的时变非线性系统, 因此人工神经网络必须能够在线训练, 以减小时变误差。传统的人工神经网络训练方法所需的数据量大, 收敛速度缓慢; 采用 Powell 方法进行人工神经网络的训练, 可以大幅度地提高收敛速度[3]。

2　基于神经网络的传感器故障检测方法的提出

考察如下纯时滞的非线性离散系统

$$x(k+1)=f[x(k),u(k-p+1)],\ y(k)=g[x(k),u(k)] \tag{1}$$

其中, u 为 m 维系统输入, y 为 n 维系统输出, x 为系统状态, $f(\cdot)$ 为非线性函数, $g(\cdot)$ 为非线性观测函数, p 为纯时滞常数。

由于系统的结构未知, 系统输入和传感器输出已知, 因此只能利用传感器的测量值及系统的输入值来寻找传感器组内各传感器测量值之间的冗余关系, 从而获得有关故障的信息。在系统正常运行过程中, 每一个传感器的测量值是系统输入及运行状态的函数, 可表示为如下的输出方程:

$$y_i(k)=g_i[x(k),u(k)]\quad (i=1,\cdots,n) \tag{2}$$

在系统是可诊断的情况下, 即系统是完全可观测的, 下式成立

$$x(k)=g^{-1}[y_i(k),u(k)]\quad (i=1,\cdots,n) \tag{3}$$

所以对任意传感器, 下式成立

$$\begin{aligned} y_i(k) &= g_i\{f[x(k-1),u(k-p)],u(k)\} \\ &= g_i\{f[g^{-1}(y_j(k-1),u(k-1)),u(k-p)],u(k)\} \\ &= \Phi_i[y_j(k-1),u(k-p),u(k-1),u(k)]\quad (j\neq i) \end{aligned} \tag{4}$$

其中, Φ_i 为一未知函数。

上述分析中, 假定系统是完全可观测的, 这一条件在实际系统中很难达到, 因此式(4)应改写为

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$y_i(k) = \Phi_i[y'(k-1), u(k-p), u(k-1), u(k)]$ (5)

其中，$y'(k) = [y_1(k), \cdots, y_{i-1}(k), y_{i+1}(k), \cdots, y_n(k)]$。

上式说明[4] 在 k 时刻，任一传感器的输出与前 p 时间段的输入和输出之间存在某一函数关系，也就是利用前 p 时间段的输入和输出可以预测 k 时刻任一传感器的输出，即存在所谓的解析余度[5]。

由于现实系统一般都是时变的，因此式(4)应当改写为

$y_i(k) = \Phi_i[y'(k-1), \cdots, y'(k-p); u(k-1), \cdots, u(k-p); t]$ (5)

也就是说，系统的解析余度是时变的。

传统的观测器方法是利用系统的数学模型通过解析计算来获得这种余度关系，但在系统结构未知的情况下，只能利用近似模型代替。由于近似模型存在建模误差和时变误差，因此难以取得良好的效果。

Cybenko 证明了具有单隐层及任意固定的连续 Sigmoid 非线性函数的多层感知器，可以以任意的精度逼近紧集上的任何连续函数。因此可以通过神经网络学习来获得系统的余度关系，建立神经网络观测器，为故障诊断提供有效信息，即所谓的神经网络观测器方法。由于系统的解析余度是时变的，因此神经网络观测器必须具备在线学习能力。

3 人工神经网络的 Powell 方法

多层感知器模型是一种典型的前馈神经网络，由输入层、隐层和输出层组成。

令 $u = [u_1, u_2, \cdots, u_m]^T$，$y = [y_1, y_2, \cdots, y_n]^T$ 分别是网络的输入、输出向量，令 $X = [x_1, x_2, \cdots, x_N]^T$ 是网络的权及阈值的全体所组成的向量。则给定 P 组输入输出训练样本 $\{(u^{(p)}, t^{(p)}) \mid p = 1, 2, \cdots, P\}$，定义网络的误差指标函数为

$$E(X) = \frac{1}{2P}\sum_{p=1}^{P} E_p(X) \quad (6)$$

$$E_p(X) = \sum_{j=1}^{n}(y_j^{(p)} - t_j^{(p)})^2 \quad (7)$$

然后就可以按照各种学习算法开始对 X 进行训练，得到最优 X_{OPT}，使得

$$E(X_{opt}) = \min E(X) = \min \sum_{i=1}^{p} f_i^2(X) \quad (8)$$

其中 $f_i(X) = y_j^{(p)} - t_j^{(p)}$。

这一过程实际上就是一个非线性函数的最优化过程，目前比较常用的神经网络训练方法是梯度最速下降法，但是该方法的收敛速度非常缓慢，虽然利用动量因子方法可以提高收敛速度，但是不能保证训练的稳定性。Powell 方法是一种比较好的非线性最优化方法，收敛速度非常快，并且收敛过程稳定。利用 Powell 方法训练神经网络，即所谓神经网络的 Powell 方法，具体训练过程如下。

(1) 给定初始点 $X^{(0)}$，精度，ε_0，$k = 0$，$t_k = 10^4$。

(2) 对 $i = 1, 2, \cdots, m$ 求 $f_i(X^{(k)})$，得向量 $f(X^{(k)})$，$= [f_1(X^{(k)}) \cdots, f_M(X^{(k)})]^T$，

对 $i = 1, 2, \cdots, m$；$j = 1, 2, \cdots, n$ 求 $X^{(k)}$ 处的商差 $J_{ij}(X^{(k)}) = \dfrac{f_i(X^{(k)}) - f_i(X^{(k-1)})}{X_j^k - X_j^{k-1}}$，得 Jacobi 矩阵 $J(X^{(k)}) = [J_{ij}(X^{(k)})]$。

(3) 解线性方程组 $[J(X^{(k)})^T J(X^{(k)}) + t_k I]\, d^{(k)} = -J(X^{(k)})^T f(X^{(k)})$，求出搜索方向 $d^{(k)}$。

在解方程组时，如果矩阵 $J(X^{(k)})^T J(X^{(k)}) + t_k I$ 的秩不等于 n，则不解方程组，而直接取 $d^{(k)}$ 为负梯度方向，即 $d^{(k)} = -\dfrac{1}{2}\nabla F(X^{(k)}) = -J(X^{(k)})^T f(X^{(k)})$。

(4) 直线搜索，$X^{(k+1)} = X^{(k)} + \lambda_k d^{(k)}$，其中 λ_k 满足

$F(X^{(k)} + \lambda_k d^{(k)}) = \min_\lambda F(X^{(k)} + \lambda d^{(k)})$

(5) 若 $\| X^{(k+1)} - X^{(k)} \| < \varepsilon_0$，则得到解 Xopt，停止计算；否则转向(6)。

(6) 若 $F(X^{(k+1)}) < F(X^{(k)})$，则令 $t_k = t_k/2$，$k = k + 1$，转向(2)；否则 $t_k = 2t_k$，转向(3)。

同传统方法比较，采用这种方法，虽然寻优过程的每一步复杂了，所用的时间多了，但收敛的速度非常快，所用的步数急剧减少。

4 基于神经网络的传感器故障检测原理

利用单层感知器为核心构造一种神经网络观测器，对传感器进行故障检测。给系统中的每一个传感器都要构造一个神经网络观测器，图 1 是传感器 1 的神经网络观测器结构。

以传感器 1 为例，神经网络观测器的输入是 $(t-p+1)$ 到 t 时刻的传感器 2 到传感器 n 的输出 Y 和系统输入，输出是 $(t+1)$ 时刻传感器 1 的预测输出 Y_1。输入序列的长度 p 应大于系统的时滞常数。

利用这 n 个神经网络观测器，可以得到 $(t+1)$

时刻传感器组的预测输出 $Y=[Y_1, \cdots, Y_n]^T$, 到$(t+1)$时刻将传感器组的预测输出Y和传感器组的实际输出$y=[y_1, \cdots, y_n]^T$进行比较, 得残差$\sigma=[\sigma_1, \cdots, \sigma_n]^T=[|Y_1-y_1|, \cdots, |Y_n-y_n|]^T$。如果任一残差大于阈值, 则该传感器出现故障。

4.1　神经网络的离线训练

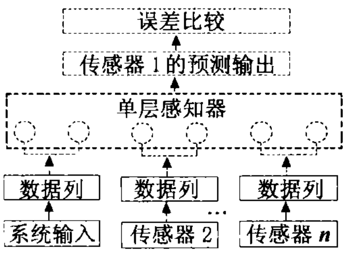

图1　传感器1的神经网络观测器

神经网络必须首先进行离线训练, 采用一组系统正常运行时的数据序列对所有神经网络进行训练, 训练时采用Powell方法。

由于神经网络离线学习, 所以学习精度可以很高。选取阈值时主要考虑实际检测过程中传感器输出噪声的影响, 应取噪声标准偏差的3～5倍。

4.2　神经网络的在线训练和故障检测

系统在线运行时, 故障检测和在线学习是同时进行的, 并以k个采用周期为循环周期, k大于p。

在1到$k-1$时刻, 进行故障检测, 并记录实际的传感器组输出序列。

在k时刻, 首先进行故障检测, 如果1到k时刻都没有故障发生, 则利用1到k时刻的传感器组输出序列对所有的传感器进行在线训练。

由于系统是动态的, 并且训练数据量较少, 阈值应取一个采样间隔内传感器输出的最大变化量与噪声标准偏差之和的3～5倍。

如果在任意时刻检测出故障, 则向操作员报警。在操作员通知故障修复前, 不进行在线训练。由于在离线和在线训练过程中, 神经网络掌握了传感器之间的冗余关系, 因此当某一传感器出现故障时, 可以利用对应神经网络观测器的预测输出代替该传感器的输出, 作为其它神经网络观测器的输入, 以发现新的传感器故障。

在控制系统中, 可以将神经网络观测器的预测输出代替出现故障的传感器的输出, 维持控制系统的正常运行。

5　试验研究

利用上述方法, 对某锅炉的主汽压力信号进行了试验。选择给水压力、锅筒压力、母管压力、给水量、给煤电机转速和主汽压力为一组传感器组。传感器软故障是在采样程序里附加固定偏值和随机分布的噪声来模拟。步长p为5, 隐层单元数为30, 学习速率为0.5。

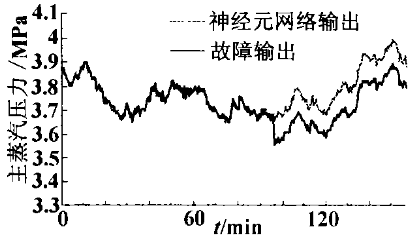

图2　输出比较

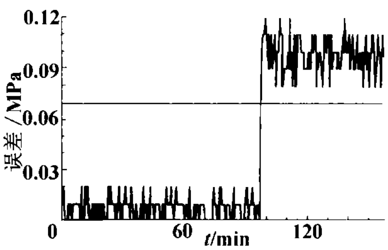

图3　误差随时间变化

图2是出现故障时的输出, 图3是对应的残差序列, 可以看到, 在故障出现后残差迅速增加, 大于阈值0.07, 显示出现故障。在传感器正常时, 残差非常小, 说明神经网络观测器的预测输出可以近似实际输出。

同时, 还对传统方法和Powell方法进行了比较, 表1是应用不同方法对神经网络进行离线训练的比较结果。比较的结果说明Powell方法的收敛速度快, 并且训练过程稳定。

表1　不同算法离线训练的比较结果

	平均迭代步数	不稳定次数	每步迭代所需时间/s
BP算法	25 000	5	0.000 5
加动量因子的BP算法	2 200	4	0.000 5
Powell方法	240	0	0.006

试验研究结果说明, 基于Powell神经网络的传感器故障检测方法可以比较好地检测多个传感器故障, 并进行信号恢复, 其训练过程迅速而且稳定, 具有非常好的应用潜力。

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(辉　编辑)

Journal of Engineering for Thermal Energy & Power. —2002, 17(1). —62～64, 72

With the use of a mathematical model featuring discrete particle movement a preliminary study was conducted of the collision of dust particles in the dust filter of a moving granule bed with filter media particles and its effect on the dust removal efficiency. The variation relationship of the number of times of collision with the system air speed was simulated and calculated. After comparison with the experimental results it has been found that with the change in the system air speed there exists a qualitative agreement between the particle collision frequency and the dust removal efficiency. The study results show that the action of collision between particles plays a major role in influencing the dust removal performance of the moving granule bed. **Key words**: discrete particles, numerical simulation, dust removal by filtration

电站锅炉系统仿真模型计算策略的研究＝**Research on the Calculation Strategy of a Simulation Model for a Utility Boiler System** [刊, 汉] / CHEN Li-jia, MA Guang-fu, WANG Zi-cai (Simulation Center of the Harbin Institute of Technology, Harbin, China, Post code: 150001) // Journal of Engineering for Thermal Energy & Power. —2002, 17(1). —65～67

The effective solution of a simulation model for a complicated system is related to the problem of how to organize the relevant complex equations of the simulation model and allocate suitable algorithms. First, the authors have identified the difference between the calculation strategy of the equations and the conception of concrete integration algorithms. This is followed by an in-depth exploratory study of two existing kinds of calculation strategy, the module-oriented and the equation-oriented, in respect of its application features as well as its merits and demerits. Also proposed is a scheme of sequential clustered calculation strategy. Finally, through a specific example of the solution for a utility boiler simulation model the superiority of the sequential clustered calculation strategy has been further demonstrated as regards its ability to attain a high-precision simulation for complicated systems. **Key words**: calculation method, equation-oriented approach, module-oriented approach

单燃烧器火焰数字图像处理与诊断方法研究＝**A Study of the Digital Image Processing and Diagnosis Method for a Single Burner Flame** [刊, 汉] / HUA Yan-ping, YU Xiang-jun, LU Zen-zhong, et al (Power Engineering Department, Southeastern University, Nanjing, China, Post Code: 210096) // Journal of Engineering for Thermal Energy & Power. —2002, 17(1). —68～72

On the basis of pulverized-coal combustion theory and digital image processing technology proposed is a method for the diagnosis of the on/off status of a burner flame. The method features three conditions, namely, the presence of a projection flame front, the irregular shifting motion of the latter's location, the variation of the latter's average gradient value. With the help of the above method it is possible to guide combustion operations and help FSSS (furnace safeguard supervisory system) to ensure furnace safety protection. **Key words**: furnace safety protection, furnace flame detection, digital image processing, flame front

传感器故障检测的 Powell 神经网络方法＝**Sensor Failure Detection Based on a Powell Neural Network Method** [刊, 汉] / LI ming, XU Xiang-dong (Department of Thermal Engineering, Tsinghua University, Beijing, China, Post Code: 100084) // Journal of Engineering for Thermal Energy & Power. —2002, 17(1). —73～75

It is essential for the control system of a large-sized thermodynamic system to detect sensor failures and then take pertinent measures to ensure the successful implementation of the control process. The authors have come up with a new type of failure detection method based on Powell neural network. Under this method a neural network observer is set up for each sensor of the thermodynamic system, which at first received an off-line training. On this basis, failure detection and on-

line training were conducted simultaneously. The neural network training by the use of the Powell method features a rapid and stable training process. It has the merits of the ability to perform on-line learning and diagnose the failure of a multiple of sensors. Actual tests on boilers show that the above method is highly effective. **Key words**: neural network, failure detection, failure diagnosis, sensor

燃气动力装置性能参数的热经济性分析与决策 = **Thermodynamic-effectiveness Analysis and Decision-making for the Performance Parameters of a Gas Power Plant** [刊, 汉] / LI Shi-wu, (Department of Aeronautical Power and Thermal Energy Engineering, Northwestern Polytechnic University, Xi'an, China, Post Code: 710071) // Journal of Engineering for Thermal Energy & Power. —2002, 17(1). —76～79, 83

Thermodynamic effectiveness features the energy utilization economy of an equipment item under the condition of its having attained a given technical objective. Through an analysis of the performance parameters of a gas power plant from the perspective of enhancing economy it has been found that thermal efficiency is not fit to serve as the decision-making index of thermodynamic effectiveness for the selection of performance parameters. By contrast it is more rational to designate the plant operating cost as a decision-making index, because it has taken into account both the design and operation factors. With a constant-pressure heating cycle-based gas turbine power plant serving as an example a thermodynamic-effectiveness optimization model has been set up along with the determination of its thermodynamic-effectiveness performance parameters. The above example can be used to prove that the seeking and use of thermodynamic-effectiveness performance parameters may be considered as a new method for the design decision-making of a gas power plant. **Key words**: gas power plant, design, thermodynamic effectiveness, decision-making

汽机调节阀阀体三维瞬态温度场及应力场分析 = **Three-dimensional Transient Temperature Field of the Valve Body of a Turbine Regulating Valve and the Analysis of Its Stress Field** [刊, 汉] / PENG Zhen-zhong, DING Zhu-shun, WANG Zhang-qi, WANG Song-ling (North China Electric Power University, Baoding, Hebei Province, China, Post Code: 071003) // Journal of Engineering for Thermal Energy & Power. —2002, 17(1). —80～83

An effective method is proposed for the modeling of a valve body with the help of a finite element method. Through the use of a structural-analysis finite element method an analytical calculation was conducted of the valve body of a main steam regulating valve for a Chinese-made 125 MW steam turbine. It includes such a variety of items as the valve body temperature field, thermal stress field, mechanical stress field and comprehensive stress field under the startup and shutdown operating conditions respectively at cold, warm and hot states. As a result, obtained were the detailed temperature field at key points under cold startup and shut-down operating conditions as well as the variation relationship of its corresponding thermal stress fields. In addition, also presented are the stress field calculation results of the valve body under the warm and hot startup and shutdown operating conditions with the loss of valve body service life being evaluated at various-state startups. **Key words**: valve body, finite element, temperature field, stress field

具有辐射边界的三维非规则域内稳态温度场分析 = **An Analysis of the Steady-state Temperature Field in a Spatial Irregular Domain with a Radiation Boundary** [刊, 汉] / LIU You-jun (Beijing Polytechnic University, Beijing, China, Post Code: 100000), FAN Hong-ming (Tsinghua University, Beijing, China, Post Code: 100084), HE Zhong-yi (Harbin Institute of Technology, Harbin, China, Post Code: 150009) // Journal of Engineering for Thermal Energy & Power. —2002, 17(1). —84～85, 89

Studied is a steady-state heat conduction problem in a spatial irregular domain with a radiation boundary. The following method has been employed to solve the problem. With variables being separated in spatial spherical coordinates obtained