第 20 卷第 5 期
2003 年 10 月

控制理论与应用
Control Theory & Applications

Vol.20 No.5
Oct. 2003

Article ID: 1000-8152(2003)05-0713-06

Application of passivity-based control in active power filters

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Abstract: When the parameters of the line and load in APF are uncertain or unknown, the system may be unstable. In order to solve this problem, the passivity-based control (PBC) was applied to the active power filters (APF). The work concentrated on the compensation strategies. The APF and the nonlinear load were considered as a whole. By simplifying the circuit of the APF by Norton equivalent, the system model on *dq* axes was built. The load voltage and the supply current were taken as the state variables of the system and the compensating current as the control variables. The passivity of the system was demonstrated. The control law, which is the reference compensation current, was deduced by the passivity approach. Though the theory was complex, the control law obtained by the passivity-base control was very simple. Some simulations are conducted with various loads, and the results indicate the stability and robustness of the PBC.

Key words: harmonics; active power filter; passivity-based control

CLC number: TP29 **Document code**: A

无源性控制在有源电力滤波器中的应用

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摘要：线路或负载参数未知可能会导致有源滤波器系统失稳．为解决系统的稳定性问题，将无源性控制应用于有源电力滤波器来保证系统的稳定性．将有源滤波器和非线性负载视为一个整体．对负载进行诺顿等效，把负载电压和电源电流作为状态变量，把补偿电流作为控制变量，建立系统在 *dq* 轴上的模型．获得系统的控制律也就获得了补偿电流的给定值．验证系统满足无源性条件之后，再利用无源性控制方法获得系统的控制律．虽然算法在理论上比较复杂，但是实现上相当简单．在仿真中，对比了容性负载，感性负载以及变动负载情况下的控制效果，仿真结果表明算法具有很好的鲁棒性，并能很好的保证系统的稳定性．

关键词：谐波；有源滤波器；无源性控制

1 Introduction

The harmonics and reactive power component of current and unbalance in three - phase system reduce the efficiency of the power system and disturb the communication network nearby. Traditionally, the passive filters, composed of resistors, inductors and capacitors, are used to eliminate the harmonics. Yet, the passive filters have many disadvantages, such as, the big sizes, fixing frequency and resonance[1]. With the development of power electronics, active power filters are introduced to address the problems. The solid-state devices as IGBT and GTO are used in APF to improve the power of the equipment. Compared with the passive filters and SVC, the APF can be controlled more easily with better performance[2]. The active power filters are taken as a controllable current source connected in parallel with the mains. The harmonics and reactive components of the load current are drawn by the APF. As a result, the supply current is sinusoidal with unity power factor.

Energy is a basic concept in both science and engineering. One complex dynamic system could be divided into many simple subsystems. The total energy of the subsystems decides the dynamics of the whole system. The passivity approach is a method using the idea of energy to design the control strategy. It includes two steps: energy shaping and damping injection. Energy shaping is to design the desired energy of the total system. Damping injection is to reform the dynamics of the

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Received date: 2003-01-10; Revised date: 2003-09-05.
Foundation item: supported by the National Key Research Foundation (1998020308).

system. Passivity-based control (PBC) makes the system more robust with simple realization[3]. Recently, PBC was applied into DC-DC converters[4], UPS[5] and hybrid generators[6] and so on.

When the parameters of the line and load in APF are uncertain or unknown, the system may be unstable[7]. The conventional compensation methods, either load current detection method or supply current detection method, are able to lead to instability. As a consequence, the research of the stability of APF system is important for its wider application. Passivity approach starts from the energy storage in the system. It designs the desired energy storage function with minimum on the desired equilibrium of the system. Thereby if the system is passive, the system will be stable on the equilibrium. Besides this, the robustness of the system is also improved.

This paper considers the APF and the loads as a whole system and the compensation current as the control signal. After demonstrating that the system is passive, this paper deduces the control law by means of passivity approach, which is the given compensation current of the APF. The results of simulation confirm the theoretical analysis and illustrate the advantage of the proposed method.

2 Brief of passivity

Consider a nonlinear system $G: u(t) \rightarrow y(t)$

$$G:\begin{cases} \dot{x} = f(x) + g(x)u, \\ y = h(x). \end{cases} \tag{1}$$

The definitions are given as follows.

Definition 1 (dissipative systems) The system is said to be dissipative with respect to the supply rate $s(u,y)$ if there exists a function $V(x) \geqslant 0$, called the storage function, such that the inequality stands for all shapes of the input function u:

$$\dot{V} \leqslant s(u,y), \ \forall t \geqslant 0. \tag{2}$$

It expresses the fact that the storage energy $V(x(t))$ of the system G at any future time t is at most equal to the sum of the storage energy $V(x(0))$ at the start time and the total externally supplied energy $\int_0^t s(u,y)\mathrm{d}t$ during the time interval $[0,t]$. Hence there can be no internal creation of energy and only internal dissipation of energy is possible. So the inequality of dissipative can be written as follows:

$$V(x(t)) \leqslant V(x(0)) + \int_0^t s(u,y)\mathrm{d}t. \tag{3}$$

If the supply rate is defined as $s(u,y) = u^{\mathrm{T}}y$, the definition of passivity and strictly passivity are given.

Definition 2 (passive systems) Suppose that the system G in (1) is dissipative with supply rate $s(u,y) = u^{\mathrm{T}}y$ and the storage function V with $V(0) = 0$, i.e. for all $t \geqslant 0$:

$$\dot{V} \leqslant u^{\mathrm{T}}y. \tag{4}$$

Then the system is passive.

Definition 3 (strictly passive systems) A system G is said to be strictly passive if it is passive and there exists a positive definite function $Q(x)$ such that for all $t \geqslant 0$:

$$\dot{V} + Q(x) \leqslant u^{\mathrm{T}}y. \tag{5}$$

3 Model of APF

The generic diagram of the active power filter discussed in the paper is shown as Fig.1.

The shunt active power filter (SAPF) is considered as an ideal controllable current source connected in parallel with the main. And the load is represented as a Norton equivalent circuit. So the equivalent circuit of SAPF is shown as Fig.2. The v_s is the supply voltage; Z_s is the impedance of the line, i_s, i_L, i_c is the supply current, load current and compensation current respectively. The current generator is the distorting current and Z_L is impedance in the equivalent circuit of the load.

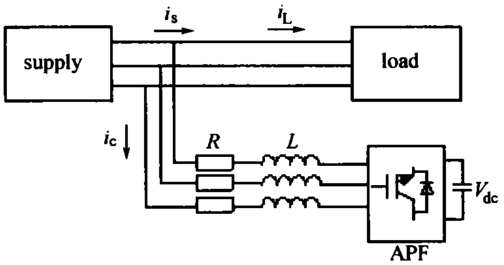


Fig. 1 Principle diagram of APF

The voltage source inverter is assumed to be driven by a high performance current control, that is, the compensation current i_c can track the referential signal i_c^*, so we only focus on how to generate the current references for the active power filter current loop. In other words, the work concentrates on the compensation strategies. According to Fig.2, assuming that the impedance is composed of inductor L_s and resistance R_s, the model of the

APF is built:

$$L_s \frac{\mathrm{d}}{\mathrm{d}t} i_s = -R_s i_s - v_L + v_s, \qquad v_L = Z_L(i_s - i_c - i_0). \tag{6}$$

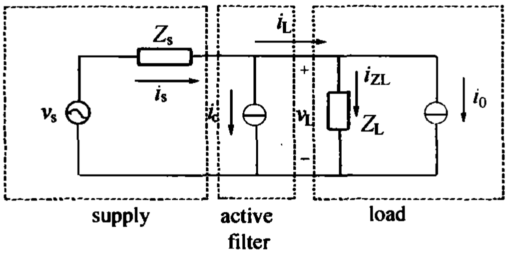


Fig. 2 Equivalent circuit of APF

4 PBC strategy

For the capacitive load, we can rewrite the model of the system:

$$L_s \frac{\mathrm{d}}{\mathrm{d}t} i_s = -R_s i_s - v_L + v_s, \qquad C_L \frac{\mathrm{d}}{\mathrm{d}t} v_L = -\frac{v_L}{R_L} + i_s - i_c - i_0, \tag{7}$$

where the C_L and R_L are the equivalent capacitor and resistance of the load respectively. On $d-q$ coordinates, the model is:

$$\begin{bmatrix} L_s & 0 & 0 & 0 \\ 0 & L_s & 0 & 0 \\ 0 & 0 & C_L & 0 \\ 0 & 0 & 0 & C_L \end{bmatrix} \frac{\mathrm{d}}{\mathrm{d}t} \begin{bmatrix} i_{sd} \\ i_{sq} \\ v_{Ld} \\ v_{Ld} \end{bmatrix} = \begin{bmatrix} -R_s & -\omega L_s & -1 & 0 \\ \omega L_s & -R_s & 0 & -1 \\ 1 & 0 & -\frac{1}{R_L} & -\omega C_L \\ 0 & 1 & \omega C_L & -\frac{1}{R_L} \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \\ v_{Ld} \\ v_{Ld} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ -1 & 0 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} i_{cd} \\ i_{cq} \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} i_{sd} \\ v_{sq} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ -1 & 0 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} i_{0d} \\ i_{0q} \end{bmatrix}. \tag{8}$$

let $x = \begin{bmatrix} i_{sd} \\ i_{sq} \\ v_{Ld} \\ v_{Ld} \end{bmatrix}$, $u = \begin{bmatrix} -i_{cd} \\ -i_{cq} \end{bmatrix}$, $y = \begin{bmatrix} v_{Ld} \\ v_{Lq} \end{bmatrix}$, then

$$\begin{cases} D\dot{x} = (J-R)x + Bu + Ew, \\ y = Cx, \end{cases} \tag{9}$$

where

$$J = \begin{bmatrix} 0 & -\omega L_s & -1 & 0 \\ \omega L_s & 0 & 0 & -1 \\ 1 & 0 & 0 & -\omega C_L \\ 0 & 1 & \omega C_L & 0 \end{bmatrix} = -J^{\mathrm{T}},$$

$$R = \begin{bmatrix} R_s & 0 & 0 & 0 \\ 0 & R_s & 0 & 0 \\ 0 & 0 & \frac{1}{R_L} & 0 \\ 0 & 0 & 0 & \frac{1}{R_L} \end{bmatrix}, \quad B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix},$$

$$C^{\mathrm{T}} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix}, \quad D = \begin{bmatrix} L_s & 0 & 0 & 0 \\ 0 & L_s & 0 & 0 \\ 0 & 0 & C_L & 0 \\ 0 & 0 & 0 & C_L \end{bmatrix},$$

$$E = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}, \quad w = \begin{bmatrix} v_{sd} \\ v_{sq} \\ i_{0d} \\ i_{0q} \end{bmatrix}.$$

The storage function is defined as

$$V(x) = \frac{1}{2} x^{\mathrm{T}} D x = \frac{1}{2} L_s i_s^2 + \frac{1}{2} C_L v_L^2. \tag{10}$$

Then the passivity of the system can be proved.

$$\dot{V} = -i_s^2 R_s + u^{\mathrm{T}} y + v_s i_s - i_0 v_L - \frac{v_L^2}{R_L}. \tag{11}$$

Suppose that the source supplies the dissipation of the load, that is

$$v_s i_s - i_0 v_L - \frac{v_L^2}{R_L} = 0, \tag{12}$$

the passivity inequality stands

$$\dot{V} < u^{\mathrm{T}} y. \tag{13}$$

The system is passive.

According to the passivity approach, the control law can be designed. Let $\tilde{i}_s = i_s - i_s^*$, $\tilde{v}_L = v_L - v_L^*$ and i_s^*, v_L^* is the reference signal of the supply current and load voltage. The model of the error is shown as follows:.

$$D\dot{\tilde{x}} = (J-R)\tilde{x} + Bu + Ew - (D\dot{x}^* - (J-R)x^*) = (J-R)\tilde{x} + \Psi, \tag{14}$$

where $\tilde{x} = \begin{bmatrix} \tilde{i}_{sd} \\ \tilde{i}_{sq} \\ \tilde{v}_{Ld} \\ \tilde{v}_{Lq} \end{bmatrix}$, $x^* = \begin{bmatrix} i_{sd}^* \\ i_{sq}^* \\ v_{Ld}^* \\ v_{Lq}^* \end{bmatrix}$,

$\Psi = Bu + Ew - (D\dot{x} - (J - R)x^*)$. For the error model, the storage function is defined as

$$V_1(x) = \frac{1}{2}\tilde{x}^{\mathrm{T}}D\tilde{x} = \frac{1}{2}L_s\tilde{i}_s^2 + \frac{1}{2}C_L\tilde{v}_L^2, \quad (15)$$

then

$$\dot{V}_1 = -\tilde{x}^{\mathrm{T}}R\tilde{x} + \Psi^{\mathrm{T}}\tilde{x}. \quad (16)$$

R, as we know, is positive definite, then if we let Ψ be the generalized control of the error system, the error system of APF is strictly passive. V_1 taking the place of the original storage function V is called energy shaping. On the other hand, V_1 can be viewed as the Lyaponov function of the system. As a consequence, if we design the control law properly to make $\dot{V}_1 \leqslant 0$, the system is stable asymptotically, that is, $\lim\limits_{t\to\infty} \tilde{x} = 0$. The next step is damping injection. Let $\Psi = K\tilde{x}$, where K is a negative definite matrix. The model of the error system is

$$D\dot{\tilde{x}} = (J - R + K)\tilde{x}. \quad (17)$$

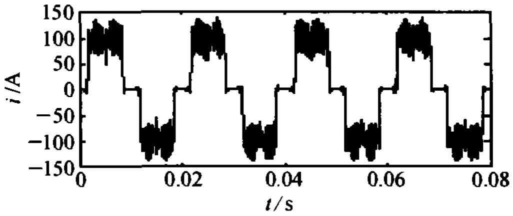
The desired equilibrium point in this control system is the complete elimination of the harmonics and reactive components in the mains. Hence the references of the line current are $i_{sd}^* = I_d, i_{sq}^* = 0$. We take $\bar{i}_d = \frac{P}{V_{sd}}$ as the RMS of the supply current, where P is the nominal power of the load. As a result, the active component of current remains and the phase of the supply current is the same as the voltage. By giving the reference current, we get the reference voltage as $v_{Ld}^* = v_{sd} - I_dR_sv_{Lq}^* = v_{sq} - \bar{\omega}L_sI_d$. The desired equilibrium of the system is $[I_d \quad 0 \quad v_{Ld}^* \quad v_{Lq}^*]$.

Let $K = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & -k & 0 \\ 0 & 0 & 0 & -k \end{bmatrix}$, where $k > 0$, the control law is given as

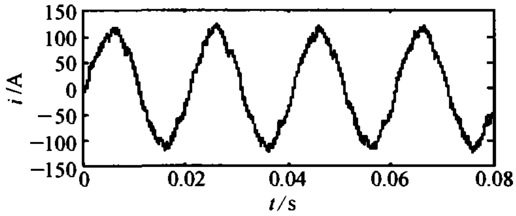
$$\begin{cases} i_{cd} = -C_L\dot{v}_{sd} - (\frac{1}{R_L} - k)v_{sd} - \omega C_Lv_{sq} + \\ \qquad (\omega^2C_LL_s + \frac{R_s}{R_L} + kR_s)I_d - i_{0d} - kv_{Ld}, \\ i_{cq} = -C_L\dot{v}_{sq} - (\frac{1}{R_L} - k)v_{sd} + \omega C_Lv_{sd} + \\ \qquad (\omega C_LR_s + \frac{\omega L_s}{R_L} + k\,\omega L_s)I_d - i_{0q} - kv_{Lq}. \end{cases} \quad (18)$$

5 Simulation results

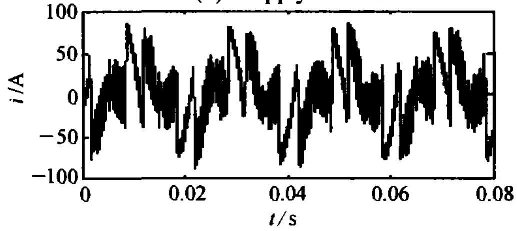
The simulations were conducted on MATLAB SIMULINK. The three loads were tested: capacitive load, inductive load and changeable load, among which a capacitive load was added to at 0.04 s and cut off at 0.06 s. The parameters of the simulation system were chosen as: the impedance of the main is $R_s = 0.19\ \Omega$, $L_s = 0.02$ mH; the impedance on the line of active power filter is $R_c = 0.2\ \Omega$, $L_c = 0.5$ mH; the DC voltage is 800 V; the solid-state devices IGBT were used. The switch frequency is 15 kHz. The nonlinear load is simulated by a three-phase rectifier bridge. The load of the rectifier bridge is 15 kW. When the load of bridge is capacitive, the results of the simulation are shown in Fig. 3. The controller can provide the line current harmonics reduction and stable operation.



(a) load current



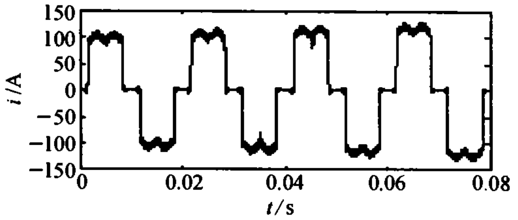
(b) supply current



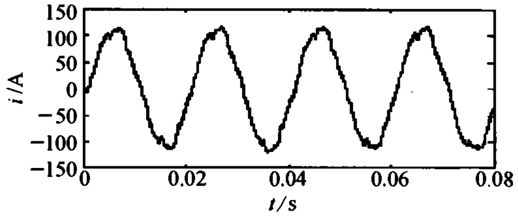
(c) compensation current

Fig. 3 Result of simulation of capacitive load

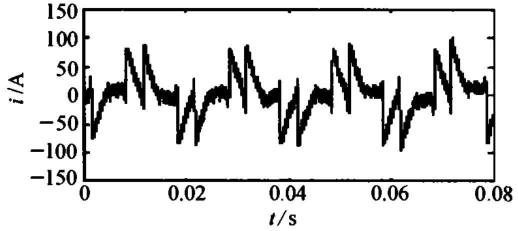
In order to test the robustness and stability of the controller, the load was changed to be inductive, but the parameters of the controller were not revised. The simulation results are shown in Fig.4. In spite of the variation of the load, the steady stability can be guaranteed. It also attests the robustness of the strategy.



(a) load current



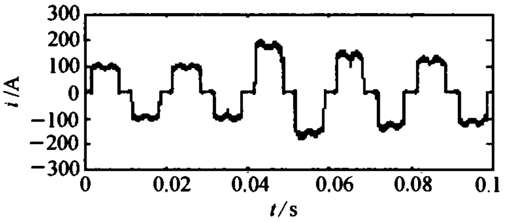
(b) supply current



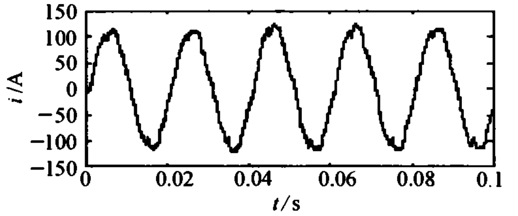
(c) compensation current

Fig. 4 Result of simulation of capacitive load

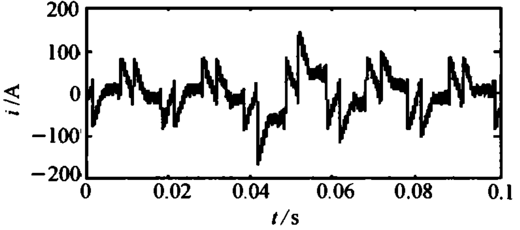
For the sake of testing the dynamic properties, the capacitive load was inserted at 0.04 s and separated at 0.06 s. The simulation results are presented in Fig.5.



(a) load current



(b) supply current



(c) compensation current

Fig. 5 Result of simulation of capacitive load

For the first case, the frequency analysis of the load current and the supply current are done. The spectrums of them are shown in Fig. 6 and Fig. 7. The results present that the fundamental components in the supply current are far larger than the load one, at the same time; the harmonics in the load current are eliminated.

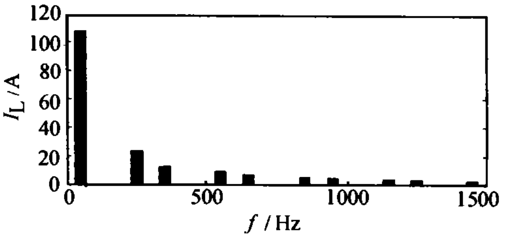


Fig. 6 Spectrum of load current

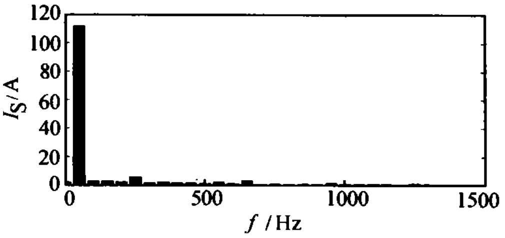


Fig. 7 Spectrum of supply current

6 Conclusion

This paper has investigated a passivity-based control for the APF systems. The proposed strategy is intended to eliminate the harmonics and reactive components of the supply current with various loads and uncertain parameters. For simplification, Norton equivalent circuit takes the place of the load. The approach is based on the model on *dq* coordinates. The passivity of the system is stated at the beginning of our design. Compared with the conventional compensation methods, the control by the passivity approach ensures the globe asymptotical stability regardless of the load parameters variations. The robustness and easy realization of the controller is also shown in the results of simulation. The APF system with passivity approach can compensate the harmonics and reactive parts of various nonlinear loads with stability and robustness.

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2003年第22届中国控制会议
会议纪要

由中国自动化学会控制理论专业委员会主办的第22届中国控制会议于2003年8月11日至14日在美丽的水电旅游城市宜昌召开.本次会议由中国科学院系统科学研究所、三峡大学电气信息学院承办.

这届中国控制会议是在新一届控制理论专业委员的组织下召开的,本次会议共收到投稿231篇,录用论文186篇,会议论文集由武汉理工大学出版社正式出版.参加会议的代表177人,其中来自国外,包括美国、日本、法国、英国、利比亚的代表12人,香港地区代表8人,两者合计占代表总数的11.3%.

会议开幕式于2003年8月11日上午在三峡大学学术报告厅举行.开幕式由大会程序委员会主席、三峡大学的崔志强教授主持.宜昌市副市长黄立鸣、三峡大学校长刘德富出席了开幕式,他们分别介绍了宜昌市和三峡大学的发展历史、现状及将来的发展蓝图;中国自动化学会副理事长郭雷院士代表中国自动化学会及中国科学院数学与系统科学研究院致辞,他回顾了中国控制会议二十多年来的历史,感谢历届控制理论专业委员会特别是秦化淑教授多年来的努力,预祝新一届控制理论专业委员会成立后进行的大量开拓性工作,包括力求使中国控制会议成为一个有影响的国际性会议的努力取得成功.在郭雷院士提议下,全体代表以长时间的热烈掌声对秦化淑教授表示由衷的感谢.最后,中国自动化学会控制理论专业委员会主任、大会程序委员会主席程代展教授汇报了第22届中国控制会议的程序和组织工作,以及控制理论专业委员会对今后中国控制会议的设想与建议.

本次大会特别邀请了5位国内外知名学者做大会报告,他们分别是美国波士顿大学的John Baillieul教授、清华大学的卢强院士、法国国家科学研究院的Romeo Ortega教授、美国加利福尼亚大学的Jie Chen教授、美国Polytechnic大学的Zhong-Ping Jiang教授.报告内容涉及理论与应用的前沿领域,反映了这些领域的最新进展和重要成果,展示了中国控制会议正在努力向有影响的国际会议的方向迈进,特邀专家的报告受到与会代表的广泛好评.会议论文分26个专题小组,包括5个邀请组报告,其中3个为English session.本次会议继承和发扬了中国控制会议严谨求实的传统,坚持以学术交流为会议的中心任务,以作为现代国际学术会议学风的一个重要指标的“No Show”率为例,在全部146人报告中,“No Show”作者12人,“No Show”率为8.2%.

作为中国控制会议重要组成部分的“关肇直奖”,其影响不断扩大,水平不断提高,本届“关肇直奖”投稿踊跃,共有8篇论文申请.本届“关肇直奖”评奖程序进一步规范化,严格化.经过专家通讯评审、初评(入围评选)、会议宣读和“关肇直奖”评奖委员会投票评选,清华大学自动化系赵千川博士的论文“Inseparability of Min-Max Systems”获本届关肇直奖;中国科学院系统科学所吕金虎博士的论文“General Complex dynamical Network Models and Its Synchronization Criterions”,香港大学Jun-min Wang博士的论文“Spectral Operators Generated by Partial Differential Equations of One-Dimensional Spatial Variable”,香港中文大学Zhiyong Chen博士等的论文“Asymptotic Tracking and Disturbance Rejection in Uncertain Nonlinear Cascaded Systems”获本届关肇直提名奖.

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8月10日晚举行了新一届控制理论专业委员会成立以来的第一次全体委员工作会议,参加会议的30多位委员皆出席了会议.在会上,程代展主任先向大家通报了专业委员会成立以来的工作情况及明年会议的筹备情况,并请上海交通大学李少远教授具体汇报承办工作的进展,然后讨论了有关控制理论专业委员会及中国控制会议今后的工作.委员们积极响应对加强专业委员会工作及中国控制会议的国际化的设想,赞同本次会议在加强国际化与规范化方面作出的努力,并提出许多建设性意见.最后会议讨论了2005年中国控制会议的申办问题.截止到2003年8月10日专业委员会收到了四川大学和华南理工大学申办2005年中国控制会议的书面申请,会上又有哈尔滨工业大学和华中科技大学提出口头申请,专业委员会对大家的积极申办表示热烈的欢迎和衷心的感谢.为使申办工作有序进行,本次会议进一步具体规范了中国控制会议的申办程序:明确申办单位需提前两年向专业委员会提交正式书面申请材料,截止时间为当年中国控制会议召开的前一周,在当年中国控制会议专业委员会全体与会委员会议上讨论决定两年后会议的承办单位.依此程序,会议最后决定2005年由华南理工大学承办第24届中国控制会议.

8月12日下午举行2003年中国控制会议闭幕式及《关肇直奖》颁奖仪式.闭幕式由控制理论专业委员会副主任王龙教授主持.《关肇直奖》评奖委员会主任郑大种教授宣布本届《关肇直奖》获奖论文.陈翰馥院士、冯纯伯院士向获奖者颁发证书和奖金.随后,控制理论专业委员会副主任郑大种教授代表控制理论专业委员会做大会总结,他感谢中国科学院系统科学研究所、三峡大学电气信息学院为会议成功所做的卓越工作和巨大努力,感谢中国技术创新有限公司对关肇直基金的赞助,感谢浙江天煌科技实业有限公司和固高科技(深圳)有限公司对大会的赞助.最后,上海交通大学李少远教授邀请大家积极参加明年在无锡召开的下一届(23届)中国控制会议.

本次会议本着严谨求实、开拓创新、积极进取的精神,在加强会议的国际化、学术性和规范化方面进行了许多积极的努力.会议的总体学术水平和组织工作受到国内外与会代表的高度评价,认为是近年来学术水平较高的一次.会后代表们游览了美丽的大小三峡和雄伟的三峡大坝工程.

中国自动化学会控制理论专业委员会
2003年9月2日