Available online at www.sciencedirect.com
SCIENCE DIRECT®
Journal of Power Sources 127 (2004) 319–324
JOURNAL OF POWER SOURCES
www.elsevier.com/locate/jpowsour

Micro-computer control for a fuel cell test bench for residential use

G. Heideck*, M. Purmann, Z. Styczynski
Institute of Power Systems, University of Magdeburg, 39106 Magdeburg, Germany

Abstract

Great efforts are presently being undertaken to develop fuel cell applications. The Chair of Electrical Power Networks and Renewable Energy Sources at the University of Magdeburg operates a fuel cell test bench which is oriented to fuel cell applications for residential use. Like many test benches of this kind, the control of the plant is done by a classical programmable logic controller (PLC). After numerous measurements and tests were carried out, it could be noted that the process power of the PLC is limited considering the improvement of dynamic behaviour of a fuel cell system and taking over extensive calculation tasks. Furthermore, an automatic measuring procedure is desirable for long-term investigations. An interface is therefore necessary for the superordinate PC-based measurement and system control in order to vary specific parameters dependent on the experimental process which have not yet been realised. Additionally, it can be noted that an economical and ecological operation of a fuel cell plant is only possible if the design considers the entire heating system. The combination of both tasks in a common control is useful. The micro-computer control as a standard solution is available for the superordinate combined control of heating systems and block-type thermal power stations using combustion engines. This control system will now be modified in close co-operation with the suppliers for the test stand control.

Keywords: Micro-computer control; Fuel cell system; Overall efficiency; Heating system; Network adjustment

1. Introduction

This paper presents a micro-computer control concept for a fuel cell test stand which enables the automatic test stand to operate and combines the fuel cell system with other system components like intermediate heat storage units or burners. The ecological, economical and technical advantages of the components can only be used by an intelligent and complex control.

An economical and efficient operation of fuel cell systems in residential applications essentially depends on the possibility to maximise the use of the generated thermal and electrical power. Reaching a high total efficiency in combination with a high electrical efficiency is the goal of the efforts. However, a high-energy output is only to be expected if an optimal ratio exists between both kinds of energy. This ratio depends on the concrete demand of heat and electrical energy and the determined price for the generated electrical power.

The fuel cell test bench at the Chair of Electric Power Networks and Renewable Energy Sources at the Otto-von-Guericke-Universitaet Magdeburg was put into operation 1 year ago. The test bench has been in operation for approximately 1500 h. More than 500 characteristics were measured. The dynamic as well as the stationary behaviour dependent on the important process parameters were recorded.

The stack is designed to generate approximately 500 W electrical power and consists of 25 single cells. Accordingly, the peripheral components are designed to supply this stack with the necessary process media. The fuel hydrogen for the stack is produced by an electrolyser which was bought in parallel with the installation of the test stand. It generates about 1 m^3/h hydrogen. For the necessary air supply of the stack, the compressed air system of the building is used. The control of the process media's hydrogen and air were overtaken by two mass flow controllers. Further parameters which determine the electrical power generation like the stack temperature and the humidity of the process media were measured by a PC-based data-acquisition system.

Table 1 shows the parameters which were actually controlled by the PLC-system S7/200 and recorded by the data-acquisition system [1].

2. Hardware description of the control

The central element of the control is the processor MPC 555 (32-bit at 40 MHz), a joint development of Motorola and IBM. It is installed on a controller board with a great number

* Corresponding author.
E-mail addresses: guenter.heideck@et.uni-magdeburg.de (G. Heideck), mathias.purmann@et.uni-magdeburg.de (M. Purmann).

0378-7753/$ – see front matter © 2003 Published by Elsevier B.V.
doi:10.1016/j.jpowsour.2003.09.029

Table 1
Measured analogue parameters and their usage

Serial number	Description	Indicated	Processed	Expensed
1	Stack voltage	×	×	×
2	Stack current	×	×	×
3	Temperature H_2 output	×		
4	Temperature H_2 input	×		
5	Temperature air humidifier	×	×	
6	Temperature cooling water heating	×		
7	Temperature heat exchanger input	×		
8	Temperature heat exchanger output	×		
9	Temperature air input	×		×
10	Temperature air output			×
11	Temperature cooling water before stack	×		×
12	Temperature cooling water after stack	×	×	×
13	Rate of flow H_2	×	×	×
14	Rate of flow Air	×	×	×
15	Rate of flow cooling water	×		×
16	Humidity air after stack			×
17	Pressure H_2 before stack	×		×
18	Pressure H_2 after stack	×	×	×
19	Pressure air before stack	×		×
20	Pressure air after stack	×	×	×

of peripheral components like external flash storage unit, real-time clock, and integrated 46-bit floating-point-unit. Most of the signals can not be directly connected to the environment. For this purpose, the board is attached to a carrier motherboard. On this carrier motherboard in addition to the power supply, are the switching elements for the adaptation and the preparation of the signals to the process as well as a set of interfaces which are necessary for communication [2].

The carrier motherboard requires only one 24 V power supply. The other necessary voltages are generated on the motherboard and for all functional units connected to the environment, separate safety devices exist.

The operation of the control unit should be made via an operator screen. An illuminated LCD display with 16 lines and 40 columns is therefore inserted. As the display has graphic capacities sequences can be directly presented. Four navigation buttons and two separate buttons are available for the input of parameters and operation modes but an alphanumeric keyboard with at maximum 7 × 8 press buttons can also be connected. The connection between keyboard and controller can be made via the communication ports. The concrete number and the kind of individual inputs and outputs can be seen in Fig. 1, which also shows the control design.

A special feature of the control is the possibility of freely mounting the analogue inputs. Additionally, sensors without signal conditioning can be connected with appropriate mounting of the board. Table 2 shows a choice of connectable sensors and the corresponding prescribed mounting. Naturally, the necessary filters for failure-free recording of the signals are considered. Several interfaces are available for communication with the environment. These interfaces are in detail:

- two serial interfaces RS 232 for the connection of a PC, a notebook or a modem;
- two CAN-Businterfaces make possible the connection of additional MPC-555 controls, other process controls with their own hardware unit and also CAN-Modules for the extension of inputs and outputs;
- an interface RS 485, used for excitation of bus capable credits such as Grundfos credits and an Ethernet interface that allows for the connection of personal computer nets and ISDN modem makes the simple entrance possible to the Internet [3].

The carrier motherboard has a size of approximately 300 mm × 300 mm and is preferably installed on the rear-side of the control cabinet behind the display so that no place is blocked on the mounting board in the control cabinet. There the necessary electromechanic and the electronic

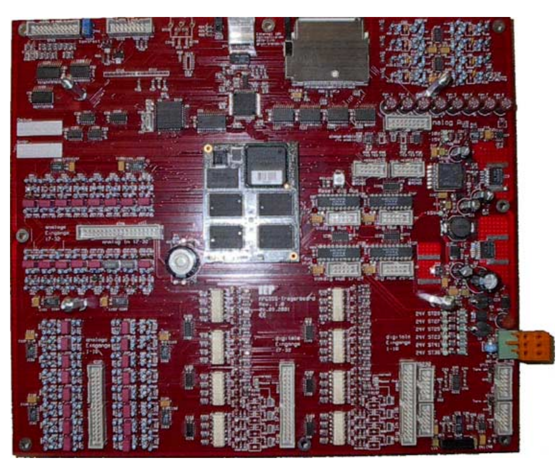

Fig. 1. Carrier board with the single modules [Foto: energiekontor Hannover].

Table 2
Choice of connectable sensors and the corresponding prescribed mounting

Serial number	Description ANAIN	Type (–)	Ra± (Ω)	R+; R− (Ω)	RF2± (Ω)	CF (μF)	RF1± (Ω)	RS (Ω)	Jumper (yes/no)	RV (Ω)
1	Temperature sensor KTY 81/210	T	800.000	1000.000	200.000	0.22	200.000	–	×	5.000
2	Temperature sensor Pt 1000	Tp	800.000	450.000	33.000	0.22	100.000	–	×	5.000
3	Switcher	K	800.000		200.000	0.22	200.000	1620	×	5.000
4	Current −20 to +20 mA	P+−	800.000	1600.000	200.000	0.22	200.000	68	×	–
5	Current 4–20 mA	IA	800.000	3200.000	200.000	0.22	200.000	156	×	–
6	Solar cell “RESOL”	12m5	200.000		5.000	0.22	5.000	100	×	
7	Gas sensor	GS	800.000	1600.000	500.000	0.22	250.000	–	×	
8	ac net voltage (isolated)	W	800.000	1600.000	49.900	0.22	250.000	127	×	–
9	Thermocouple Type K	NCN	800.000	10000.000	1.000	0.22	5.000	100	×	–
10	Voltage of Lambdasonde	L	1000.000		100.000	1.00	100.000	250000	–	–
11	dc voltage 30 V	30U	200.000		200.000	0.22	1000.000	–	×	–

Amplifier resistor: Ra, R+, and R−; filter capacitor/resistor: CF, RF2, RF1; shunt: RS; pull-up resistor: RV.

Fig. 2. Implemented microcontroller solution with input/output and switching modules [Foto: energiekontor Hannover].

components for the load circuits including the 24 V power unit can be installed (Fig. 2) [4].

3. Software description

The designer of the hardware has developed this control as a superordinate control system for innovative power stations, e.g. with condensing boiler cascades, block-type power stations, intermediate storage units, solar facilities, and heat pumps as well as heating circuits and hot water preparation with low return pipe temperatures. The ecological, economical and technical advantages of the components can only be used effectively by using such a complex control system. For the processor MPC555 different operating systems like Linux, RTOS and software programs like software codes written with the programming language C can be used. The developers have decided to use the multitasking operating system “Real TimeOperatingSystem-Uni Hannover” (RTOS-UH). The operating system is responsible for the internal organisation of the computer system and very often makes possible the further use of older program codes or codes which are written by changing software teams. The present program is written in the standard language PEARL which was specifically developed for control and supervisory tasks. In order to use as many tools as possible of available software and the extensive experiences of the software developers, the team at LENA also decided to use the standard language “PEARL”. Software tools like voltage, frequency and power monitoring for the combined heat and power unit (CHP) can almost be incorporated into the program of the fuel cell system without adaptation. Bugs can be limited and the development time can be shortened by using proven software tools. C-Compiler for the operating system RTOS-UH are available, so that parts of the program which are written in the programming language C and/or C++ and run under Windows or Linux run also under RTOS-UH. In this way, C-code can be imbedded without problems into the PEARL program. The chosen display provides a menu control working nearly exclusively with plaintext. So the operation can be significantly improved. Linearities can also be presented with a good resolution on account of the graphical capabilities of the display. Therefore, programmed day or week load curves can be visualised. The real-time clock with an integrated calendar supplies the system with the desired real-time references. The extensively programmed disturbance and alarm management also uses the possibilities of the real-time clock and is helpful for limiting downtimes during the operation of the fuel cell system. The extensive remote control possibilities are discussed in one of the following sections [4].

4. Planned extensions

4.1. Hydrogen humidification

For the expansion of stack investigations a humidifier for hydrogen was planned and constructed according to the concept of the air humidifier. In this manner, it is possible to determine the dependence of the power generation on the humidification degree of hydrogen and to optimally control the humidity. The possible water mass transported by the air mainly depends on the temperature of the hydrogen so that the water content can be specified by controlling the humidifier temperature. It is, however, necessary that the tube between the humidifier and the stack is well insulated to prevent a cooling of the hydrogen and therefore a condensation of the water on the way to the stack. Otherwise, the tube has to be additionally heated between humidifier and stack. Therefore, the heating control can be overtaken by the supervisory control.

4.2. Air supply

The existing test stand is supplied with air from the compressed air system of the building. A mass flow controller regulates the air flow in accordance with the set point defaulted by the PLC. Since fuel cell facilities for residential use generally use the compressed air generated by their own compressors, the air supply of the system will be conceptually adapted. An air compressor with a power control was chosen to supply the fuel cell system with low energy consumption and low pressure losses. It was particular about high efficiencies under full and part load at the selection of the compressor and the motor. However, in the case of this concept, the control must generate the required actuator signal. For this purpose, the volume flow and the temperature of the air are to be measured. Fig. 3 shows the construction of the new air system.

4.3. Heating integration

The main goal of the integration of a stationary fuel cell system into a heating system is the full use of generated heat to improve the total energy balance. The best way to achieve the defined goal is the operation of the heating system at low return pipe temperatures. A low return pipe temperature allows the cooling of the waste air below the dew point. Additionally, a higher temperature difference between the stack and heating circuit can be reached. The stack temperature of a PEM fuel cell is often situated between 60 and 80 °C. A heat exchanger is necessary for decoupling the pressure levels of the heating system and the stack. In order to limit the size of the exchanger a temperature difference of 10 K between supply temperature of the fuel cell and supply temperature of the heating circuit has to be considered. So only supply temperatures of 60 °C without additional heating can be reached. This value is still acceptable for low-temperature heating systems and hot water preparation. In order to be more independent of the fuel cell temperature there is the idea to use surplus hydrogen in a catalytic burner and therefore to raise the temperature level. Simultaneously, it is possible to influence the ratio between heat and electrical power generation and to meet the demand of heat and electrical power. This is a difficult task for the proposed control since the control parameters must be permanently matched.

In order to improve the number of full operating hours and to make possible a more effective power generation during peak load times without wasting heat the installation of an intermediate heat storage unit can be economically and ecologically promising. The storage unit can be also used for pre-warming the stack. However, for this purpose an additional three-way valve and a connection to the upper part of the heat exchanger is necessary. If the rotation speed of the pumps are controlled via a pulse width modulation (PWM) the storage unit can be optionally charged and discharged. Fig. 4 shows the scheme of the test bench which is extended by the corresponding components. For the control of the energy fluxes a complex control system is required which precisely knows the system conditions. The mentioned micro-computer control is designed for this task.

4.4. Grid-connection/power supply monitoring

The investigations on the test bench are focused on the grid connected operation. In this operating mode, the generated electric energy is used to cover the local internal consumption, e.g. in a house. The surplus is then fed into the electric power network of the grid utility and compensated. The actual benefit results in the decreased purchase of electric energy since the compensation for the fed-in electric energy is lower than the price of the purchased energy. However, the generated electric power can only be reasonably used if it conforms to the parameters of the power network. For this reason, direct current of the fuel cell with a low voltage level has to be transformed into alternating current on a higher voltage level. While the adaptation of the kind

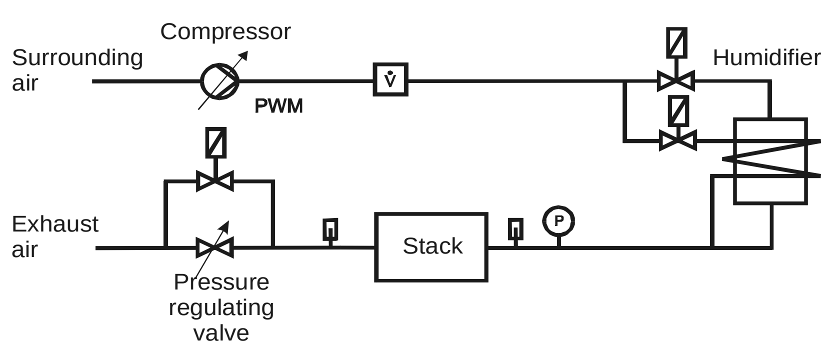

Fig. 3. Scheme of the planned air supply.

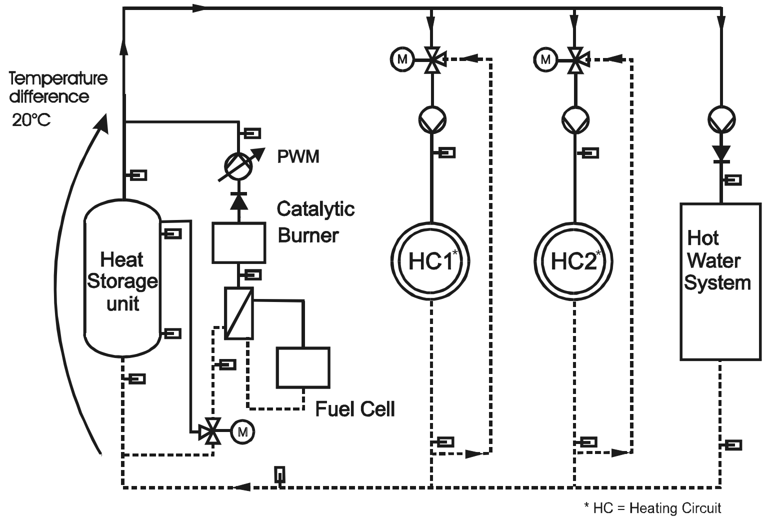

Fig. 4. Scheme of the superordinate heating system of the fuel cell test stand.

of current is solved by well-known concepts of inverters, the low voltage level of the fuel cell proves more problematic. The fuel cell stack which is integrated into the test stand has an open-circuit voltage at about 23 V and a voltage of about 12 V under full load. For a single-phase operation a voltage level is required which is approximately 30 times higher than the voltage level of the fuel cell. The converter used at the chair consists of a boost converter and an inverter. This concept results in a relatively low efficiency caused by the voltage adaptation. Therefore, it is planned to increase the dc voltage of the fuel cell to a dc voltage of 400 V by using a step-up switching regulator and to transform the direct current into an alternating current by installing a standard inverter. The step-up switching regulator and the inverted rectifiers can be directly controlled with the described micro-computer control. Fig. 5 shows the block diagram of this concept by which a higher efficiency is expected [5].

4.5. Remote monitoring

Service and fast reaction when problems occur are increasingly becoming important sales arguments. This has resulted in the use of remote monitoring and modern disturbance management. With the available Ethernet interface, the connection of an ISDN modem is both easy and possible. Remote monitoring, remote control and remote diagnostics are realisable both via the Internet and directly via the telephone network. The necessary software tools are available. A visualisation of the process for the clear observation of the fuel cell system is planned.

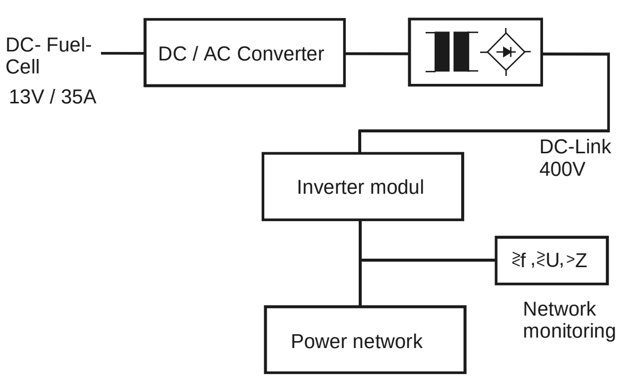

Fig. 5. Block diagram of the concept for voltage and current adaptation.

5. Conclusion

Beginning with the problems during the studies on a fuel cell test bench at the Chair of Electric Power Networks and Renewable Energy Sources, a micro-computer control was presented which can be used for installation into the test bench as well as for commercial applications. On account of its complexity, the control can also simultaneously be used for the superordinate heat system and the transformation of the electrical energy of the fuel cell into conform power of the power network. Since all of the system information is concentrated in the control, the single components can be optimally operated in their respective operating points for reaching a high total efficiency. An adaptation to the desired case of application is possible at any time via the open hardware concept. By the choice of this control, which is mainly planned for innovative power stations and with already available software tools, a low-cost solution was found. In the second part of the paper, the advantages of the leading micro-computer control were demonstrated at selected control tasks.

References

[1] Technical documentation of the fuel cell test bench at the Chair Electric Power Networks and Renewable Energy Sources of the University Magdeburg issued by the Firme ZSW in Ulm, http://www.zsw-bw.de.

[2] 2002 Product catalog of the firm PHYTEC Technology Holding AG, http://www.phytec.de.
[3] Technical documentation “phy555 Trägerboard” of the firm IEP Ingenieurbüro für Echzeitprogrammierung Hannover, as of 12 October 2001, http://www.iep.de.
[4] Technical brochure of the firm energiekontor in H annover, http://www.energiekontor-hannover.de, 8 April 2002.
[5] Test report about the sinus inverter in the fuel cell test stand at the Chair Electric Power Networks and Renewable Energy Sources, COO.1000.1600.2.58861-1, 5 November 2001.