Simulation Structure for Simulation Model of MCFC–GT Hybrid System*

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Abstract: The control system of MCFC coupled with a gas turbine should be based on the multi–layer structure, (two or three–layers), wherein the third layer relates to the power output from the system and can be considered separately. Simulation model of MCFC–GT hybrid system was built. The simulator is based on a zero-dimensional modelling of the individual elements of the system. The simulator was used for mapping the main components behaviour (MCFC and GT separately). Based on the obtained maps of the performances and adopted restrictions on technical–operational nature the operation line for the first line of the control strategy was obtained. The presented results indicate that the analysed MCFC–GT Hybrid System possesses a high operation and control flexibility while at the same time maintaining stable thermal efficiency. Operation of the system is possible over a wide range of parameter changes.

1 INTRODUCTION

Presently, most energy is produced by large baseload power plants (Kawabata et al., 2012) and distributed to customers via a grid. In the future the energy distribution system will probably take a radically different form—it will be composed of many small units connected to a network called distribution generation (DG).

DG is a system of energy distribution where the energy is produced locally. A connection to the grid allows energy to be bought from and sold to other customers. Energy sources for DG will have to meet certain requirements: appropriate range of power output, electrical efficiency—which are higher than presently obtained by large power plants, acceptable costs of installation, possibility of using standard fuels.

Most of the requirements are met by fuel cell hybrid systems (HS), which are a combination of a fuel cell module and gas turbine system and utilized for power generation, combined heat, and power, and even triple–generation. Hydrogen is the most promising energy carrier for future applications. There are many types of fuel cells, two of them are high temperature: Molten Carbonate Fuel Cell (Ramandi et al., 2014; Razbani and Assadi, 2014; Sheng et al., 2006; Wee, 2014)—MCFC—and Solid Oxide Fuel Cell (Ding et al., 2014; Razbani and Assadi, 2014; Xu et al., 2014) —SOFC. Solid Oxide Fuel Cells (SOFCs) are potential sources for this system of energy conversion due to their high efficiency and possibility of direct use of hydrocarbons. Moreover, their high working temperature allows for the possibility of using lower-cost catalysts (Ni vs. Pt), standard fuels (even biofuels) and the possibility of adding a gas turbine subsystem to increase total efficiency.

Control strategy is an important element in designing any system of this kind and it constitutes a significant part of the modeling work done. Off-design (part-load) analysis is an important issue for any type of system involving MCFC–HS and should be considered when designing and defining the operational characteristics. A proper off-design map of performance underscores control strategy design. Results drawn from system behavior analysis at part load conditions should aid in defining the system structure and its nominal parameters, as well as the constructional solution and characteristics of a given subsystem.

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Bedont et al. (Bedont et al., 2003) investigated off-design performance of a hybrid system based on an existing 100 kW MCFC stack. Chen et al. (Chen et al., 2006) show that the generating efficiency of the MCFC-HS (≈ 13 kW) is close to 60% at the design point and over 56% at part load conditions. A few dynamic response investigations of the MCFC can be found in (He, 1998; Kang et al., 2001; Sheng et al., 2006; Yang et al., 2019). The paper (Iora et al., 2010) presents a model for the off-design analysis of a hybrid plant based on a MCFC and a gas-turbine. The model is used to define a possible regulation strategy for the power plant, minimizing the performance decay at partial load and allowing investigation of the interaction issues among the different plant components. The results indicate the possibility to effectively regulate the plant power output acting on the turbine shaft speed, the air-to-fuel ratio, the bypass of cathode air, and the fuel utilization, achieving very high part-load efficiency and respecting constraints on the admitted operating range for the plant components. In (J Milewski and Miller, 2012) the results of mathematical modeling and numerical simulations of the off-design (part-load) operation of the molten carbonate fuel cell hybrid system (MCFC-HS) are set out. The governing equations of modeling are given and an adequate simulator of the MCFC stack was made and described. The performance of the MCFC-HS with part- and over-load operation is shown, and adequate maps are given and described.

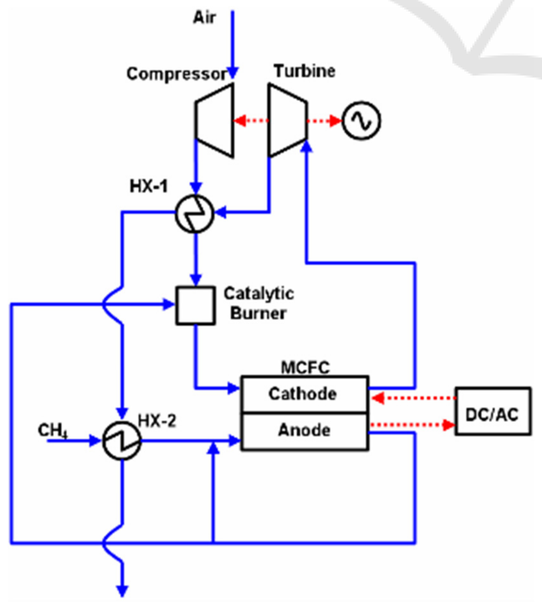

Figure 1: The configuration of MCFC–GT Hybrid System.

In this control strategy study for MCFC-HS, use was made of methodology and experience of the Institute of Heat Engineering (Warsaw University of Technology). Institute of Heat Engineering methodology was utilized in the mathematical modeling of the “classic” system elements (e.g., compressor, turbine, heat exchanger). HYSYS.Plant (“HYSYS.Plant Steady State Modelling,” 1998) software was used for modeling and simulations.

The results presented in this paper concern a larger system (3 MW), which can be utilized for office building applications. An axial turbine can replace the radial turbine for this range of power.

2 MOLTEN CARBONATE FUEL CELL–GAS TURBINE HYBRID SYSTEM

The planar MCFC has pre-commercial applications (100 kW to 2.8 MW) which include the methane–fueled MCFC Module (MCFC-M) as the main object. The fuel cell stack, heat exchangers, mixing chamber, blower, pre-reforming plenum and re-cycle plenum are placed inside the MCFC-M. The Molten Carbonate Fuel Cell—Hybrid System consists of the following elements:

Table 1: Nominal parameters of the MCFC-GT hybrid system (Milewski et al., 2010; Jarosław Milewski and Miller, 2012).

Parameter	Value
Overall Efficiency (LHV), %	58
Re-cycle Factor	44
Excess Air Factor	1.68
Average Cell Voltage, V	0.66
DC/AC inverter efficiency, %	95
Electric generator efficiency, %	99
Mechanical efficiency of the GT, %	99
Electric motor efficiency, %	95
Turbine Inlet Temperature (TIT), ○ C	650
Compressor pressure ratio	8.35
Fuel cell electrolyte material	Li/Na
Electrolyte matrix thickness, mm	1

- Air Compressor
- Fuel Compressor
- Gas Turbine
- Air Heater
- Fuel Heater
- MCFC Module

The stack consists of parallel, and series connected cells. The singular cell consists of three main layers: anode, electrolyte, and cathode. The electrolyte is kept by a matrix, which provides cell support. Proper and efficient operation of the MCFC module requires additional devices.

Process air is delivered to the MCFC at an elevated temperature and flows through the heat exchanger. Air then flows through the stack and escapes on the other side. Finally, it enters the combustion plenum where the remaining non-oxidized components are utilized.

Excess power from the compressor turbine subsystem is converted into electricity. HS efficiency is given by the equation:

$$\eta_{HS} = \frac{P_{MCFC} \cdot \eta_{DC-AC} + (P_T - P_{C,air}) \cdot \eta_g \cdot \eta_m - P_{C,fuel}}{n_{fuel} \cdot HHV_{fuel}}$$

where: η —efficiency; g —electric generator; m —mechanical; C —compressor; n —molar flow, kmol/s; HHV —Higher Heating Value, kJ/kmol; DC-AC —DC/AC inverter.

Based on 0 D mathematical modeling the design point parameters of the system presented in Fig. 1 were estimated; they were obtained by the researchers' own calculations based on an adequate mathematical model (Milewski et al., 2013). During the simulation the electrolyte matrix thickness and electrolyte materials assumed were 1 mm and Li/Na, respectively. The main system parameters are presented in Table 1.

3 THE CONTROL STRATEGY

Mathematical modeling is now the basic method for analyzing systems incorporating fuel cells. A zero-dimensional approach is used for the modeling of system elements. Mathematical models of MCFC, and other system elements as well as the control strategy for MCFC–GT based on triple–layer control system is presented in our previous works (Milewski et al., 2010; Jarosław Milewski and Miller, 2012). As the results of the previous works adequate maps of performances were obtained with indicated the control line of the system. In general, it should be underlined that in the case of a system with a pressurized MCFC and gas turbine set there is a possibility of changing the system power output by changing not only the amount of fuel but also the voltage and the MCFC current at variable rotational speeds of the compressor-turbine unit. This is accompanied by varying system efficiencies. Hence there is a need to formulate an appropriate control concept (control strategy logic) and approach for technical realization.

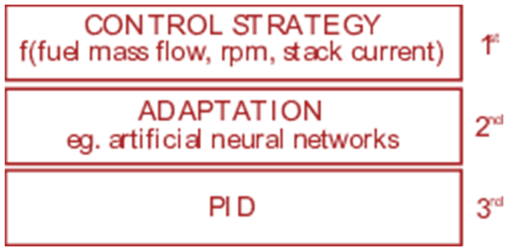

Figure 2: Triple-layer control system.

A triple layer control system is proposed for MCFC-HS operation control. The system consists of three layers: Control Strategy, Adaptation, and Regulation (see Fig. 2).

The first layer is responsible for safe and efficient operation of the whole hybrid system. Adequate functional relationships between all controlled parameters and constraints should be applied. The adaptation layer is responsible for making corrections to first layer characteristics due to the degradation of system elements. The last layer of the control system acts in dynamic mode to realize the control strategy.

The control strategy is based on three functional relationships:

$$m_{Fuel} = f(P_{HS})$$

$$n = f(P_{HS})$$

$$I_{MCFC} = f(P_{HS})$$

where: P_{HS} —is power demanded by an external load.

Approximately, 16,000 system operation points (state points) were found. Every state point is defined by three independent parameters: delivered fuel flow, rotational speed of compressor-turbine subsystem, and stack current. The other flow and electric parameters were collected for these three parameters. This data set was analyzed, and it was found that the best system performances are obtained at the highest values of fuel utilization factor. The highest possible fuel utilization factor was found to be 90%. This means that fuel flow can be correlated with used electric current from the stack by the following relationships:

$$\frac{I}{m_{Fuel}} = const$$

$$\frac{I_{stack}}{I_{stack,max}} = a \cdot P_{MCFC-HS} + b \qquad (1)$$

$$\frac{m_{fuel}}{m_{fuel,max}} = a \cdot P_{MCFC-HS} + b \qquad (2)$$

where: a and b —linear regression factors. The linear regression factors a and b are: $2.1 \cdot 10^{-4}$ and $8.69 \cdot 10^{-2}$.

The maps presented below include the values of parameters for constant fuel utilization factor of 90%.

Adequate maps of performance were generated by a MCFC–GT Hybrid System simulator using 0 D mathematical modeling. The operation line of MCFC–GT Hybrid System was determined based on in-depth analysis of the maps obtained. The best performance and safe operation of the system can be achieved with constant fuel utilization factor (at the highest possible value). Setting the constant fuel utilization factor at 90% appears acceptable and adequate relationships are proposed (1 and 2). Thus, the obtained relationships are used in the first layer of the triple layer control system.

The second layer is needed for adaptation of the control strategy to changes in external environments (fuel quality, single element degradations, etc.). The long operation of the MCFC–GT Hybrid System is not the subject of the paper; thus, this layer remains empty.

4 THE CONTROL SYSTEM

The third layer of the control system is responsible for dynamic operation of the system and requires to be built as the control system of the unit. The control strategy can be realized based on various architectures, in this paper we propose to use internal DC micro network to balance the power between MCFC stack and gas turbine subsystem.

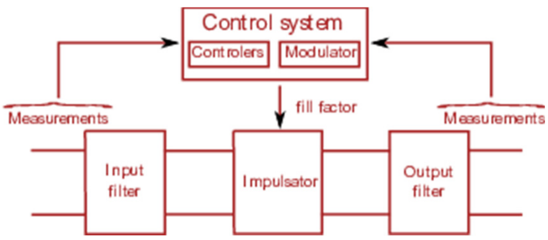

Figure 3: The general structure of DC/DC converter.

The control system is based on DC/DC converters, which can be classified in various ways, but generally they possess the similar structure as shown in Fig. 3. Two major subsystems can be distinguished here the power circuit and control circuit. The heart of the control circuit regulators is selected signal (voltage, current or power, input or output, or any combination of these), depending on the application, and the modulator. Power circuit consists of an input filter, the encoder system transformer and rectifier (in some types of converters, for example in the breastbone) and output filter.

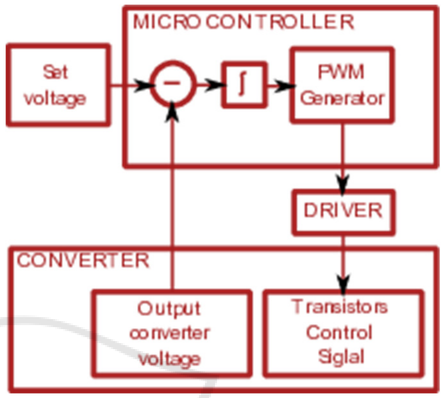

Figure 4: Block scheme of single unit controller.

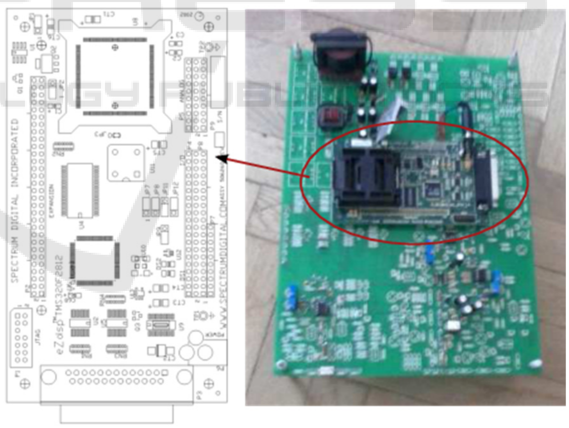

Figure 5: Texas Instruments TMS320F2812 controller.

Currently control systems for complex circuitry, such as hybrid systems that use different sources of energy, the building blocks of the special signal processors DSP, commercially available controller (Texas Instruments TMS320F2812—see Fig. 5) was used. The main tasks of the used controller in the hybrid system control are:

- measurements of currents and voltages of each local devices

- if necessary, modifying the control signal to ensure constant current–voltage conditions at the output resulting from the setpoints coming from the main controller.
- transmission of information on the operation of the inverter by using external interfaces
- possibility to change the setting operation of the inverter via the external interface.

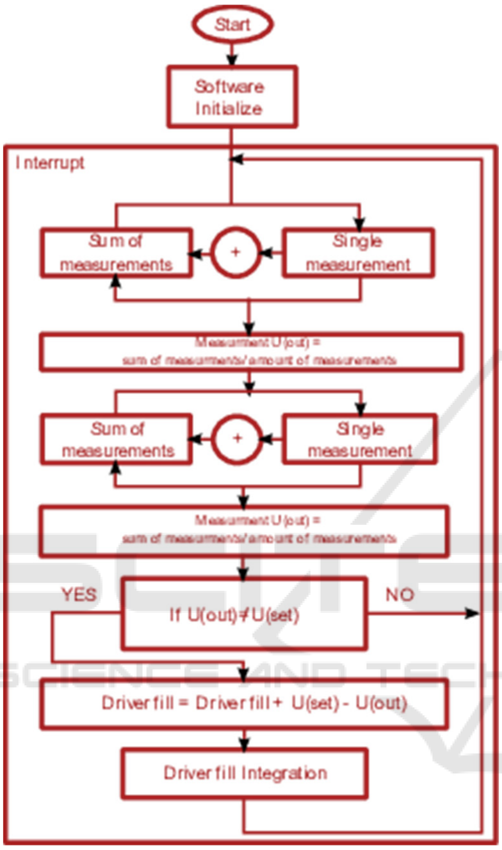

Figure 6: Block scheme of the algorithm implemented in the single unit controller.

The designed control system was achieved on the processor TMS320F281 calling the timer interrupt every 50 microseconds (see Fig. 6). The discontinuation of this measurement is made, integration and correction of the width of the rectangular waveform. This is sufficient because the frequent measurement gives the ability to quickly respond to changing output parameters. PWM signal generation takes place outside the main program. It is independent of the computational process. Thus, when conducting the calculation of new settings waveforms are still generated from a predetermined frequency—typically 10 .. 30 kHz.

A good idea is also to use multiple interfaces, e.g. ISP for communication and RJ-45 interface to make simple changes or reading an information from master (external) controller, as implemented in MCFC–GT hybrid system—Fig. 7. The used microcontroller (TMS320F2812) cannot be connected in a simple way to Ethernet interface, and since it is necessary to realize the communication between CPU to the local actuators, it was decided to apply additional microcontroller for a web server function. Fig. 8 presents the view motherboard with integrated microcontroller ATMEGA 128 carrying out the functions of the web server.

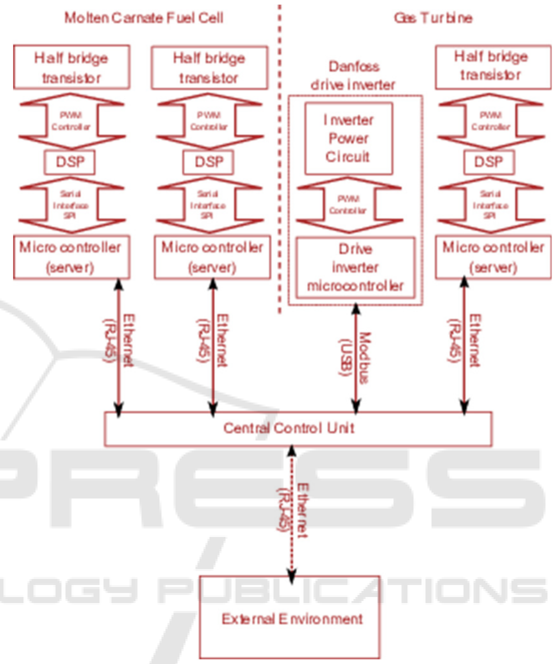

Figure 7: The structure of the communication between the MCFC module and gas turbine sub-system by the control system.

Figure 8: A view of motherboard which integrating a microcontroller ATMEGA 128 16 MHz with Ethernet controller RTL1819AS IEEE 802.3 10Mb/s for carrying out the function of a web server.

The main assumptions designed control system, using several communication interfaces, standards, and protocols (Ethernet, SPI, ModBus) for communication between components of MCFC-GT hybrid system are as follows:

- Power electronics inverter control for simulating MCFC behavior based on signals from the CPU based on two cooperating microcontrollers ATMEGA 128 and TMS320F2812, one of whom one acts as server and the other is responsible for the stable operation of the inverter.
- Classic serial interface was used for the communication between TMS320F2812 and a microprocessor (server). Interface is relatively simple to use, the amount of information sent by it will not be large, and the distance between the two processors will be the order of centimeters, so there is no significant risk of interference between the control signals.
- Gas Turbine subsystem controller is a microcontroller Danfoss drive, see Fig. 9
- Drivers of power electronic converters enable parallel operation of both components (MCFC and gas turbine set) are based on two cooperating microcontrollers, one of which acts as a server and the other is responsible for the stable operation of the inverter.
- Communication between the central control unit and the controller of the MCFC and the driver circuits enable parallel operation is realized by Ethernet.
- Communication between the central control unit and the Gas Turbine set controller (drive inverter) is implemented using the ModBus protocol.

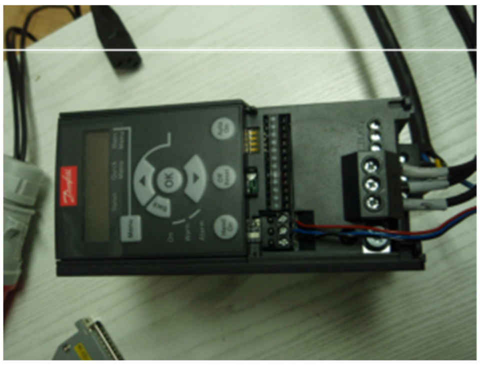

Figure 9: Danfoss drive inverter.

The control system was implemented into software–hardware simulator of the MCFC–GT hybrid system which is composed by the following elements:

- two power electronics inverters AC/DC with half-bridge topology with power 2 kW each
- one power electronics inverter DC/DC with half-bridge topology with a power of 2 kW
- hardware model of Gas Turbine set consisting of a three-phase synchronous motor and three-phase synchronous generator mechanically connected.

Figure 10: Ga Turbine set hardware–based model with an inverter drive by Danfoss.

For mapping the MCFC behavior the two power electronic converters are used, whereby one (AC/DC converter) simulates the fuel cell and the second (DC/DC) is responsible for cooperation with the turbomachinery. The simulating of the air compressor–gas turbine–generator required the statement of both machines in the system gas turbine

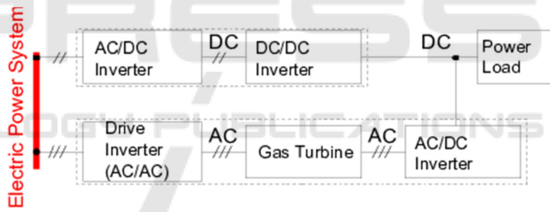

Figure 11: Scheme of the electric system of the simulator.

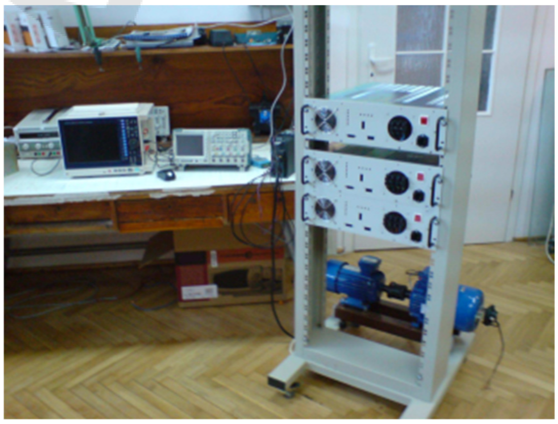

Figure 12: The simulator with connected measurements and data acquisition instrumentation.

set (engine shaft connected to the shaft of the generator by using a coupling). For powering a model of gas turbine set, the Danfoss drive inverter with a power of 2.2 kW is used—see Fig. Turbine with an inverter drive the company Danfoss.

The output synchronous generator connected with the AC/DC inverter is responsible for cooperation with MCFC. Schematic diagram of the electrical part of the simulator is shown in Fig. 11. Initially it was assumed that the system would operate with an external electric power system, but ultimately limited to a DC power receiver. Fig. 12 shows the view of the built simulator with measurements and data acquisition instrumentation.

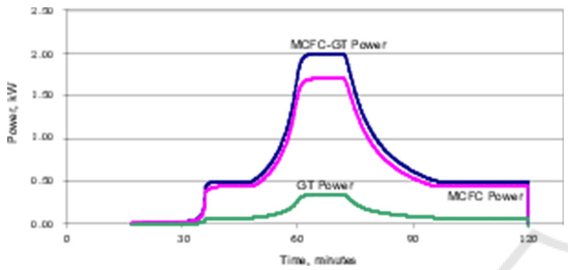

Figure 13: The measured power generated by the system and the corresponding equipment obtained using the control system.

The control system and hardware–software simulator was developed from a series-manufactured components. The simulator was controlled by the control system with implemented the control strategy. Fig. 13 presents the power as a function of time recorded during the tests under load by the assembled system.

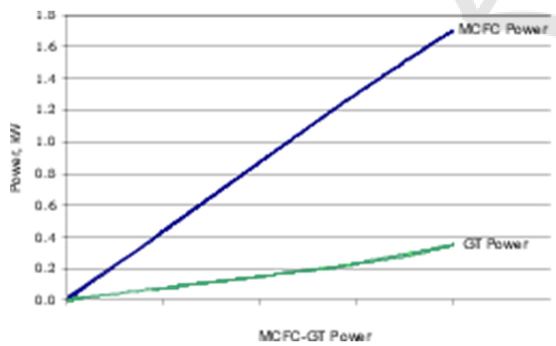

Figure 14: MCFC and Gas Turbine set powers as functions of total system power (MCFC–GT).

Fig. 14 presents the dependence of the particular components that make up the MCFC-GT hybrid system as a function of output power (compare against Eqs (1) and (2)). The curves in Figs 13 and 14 confirm the correctness and validity of the control strategy carried out, simulation and constructed mathematical models.

5 CONCLUSIONS

The control system of MCFC coupled with a gas turbine should be based on the multi–layer structure, (two or three-layers), wherein the third layer relates to the power output from the system and can be considered separately.

Simulation model of MCFC–GT hybrid system was built. The simulator is based on a zero-dimensional modeling of the individual elements of the system. The simulator was used for mapping the main components behavior (MCFC and GT separately).

Based on the obtained maps of the performances and adopted restrictions on technical–operational nature the operation line for the first line of the control strategy was obtained. The highest system efficiency is achieved by working at the highest possible fuel utilization in the MCFC stack. It was assumed that the limit value of this parameter is 90%. Adequate relationships are proposed for achieving this assumption (see Eqs (1) and (2))—the fuel amount delivered to the system is in proportion to the amount of electric current drawn from the MCFC stack. Maintaining the safe and efficient operation of the system is realized by gas turbine set in this case, the gas turbine subsystem, what is obtained by appropriate changes in the rotational speed of the shaft.

The control system which realizes the obtained control strategy was built. Then, hardware-based models of the main elements were created based on the electric equipment. The gas turbine was simulated by coupled electric engine and electric motor powered by driver inverter. The MCFC was simulated by programmed micro-controller for giving current–voltage characteristics. The hardware–software model was connected to the control system and adequate simulations were performed.

The presented results indicate that the analyzed MCFC–GT Hybrid System possesses a high operation and control flexibility while at the same time maintaining stable thermal efficiency. Operation of the system is possible over a wide range of parameter changes.

The presented control strategy offers some practical advantages, which include maintaining the operating point at a possibly high level of efficiency even under changed operating conditions. Furthermore, it is possible to separate the overriding control layer (layer III) from the global strategy of such a system.

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