Wind turbine control research in the Laboratory for renewable energy sources

Nedjeljko Perić[1], Mate Jelavić[2], Željko Ban[1], Hrvoje Domitrović[1], Branimir Matijašević[3], Milan Kostelac[3], Stjepan Mikac

[1] Faculty of Electrical Engineering and Computing, University of Zagreb, Croatia
[2] Končar – Electrical Engineering Institute, Zagreb, Croatia
[3] Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Croatia

Contact: nedjeljko.peric@fer.hr Phone: +385 1 6129 855 Fax: +385 1 6129 809

Abstract: This paper presents the Laboratory for renewable energy sources (LARES) at the Faculty of Electrical Engineering and Computing, University of Zagreb, Croatia, with emphasis put on the laboratory wind turbine development and testing. The laboratory consists of a micro grid comprising wind turbine, hydrogen fuel cells and an array of solar panels. Wind turbine is definitely the most complex subsystem in this setup and its development was a very demanding task. Almost two years of development resulted in a realistic model of pitch controlled variable speed wind turbine that allows for investigation of various pitch and torque control concepts.

1. Introduction

Wind turbine and wind farm control has been one of main research interests at the Faculty of Electrical Engineering and Computing, University of Zagreb, Croatia, for past six years. In this period many advanced wind turbine control and estimation algorithms have been developed and tested using professional simulation tools such as GH Bladed. [1, 3, 4, 7, 10, 14]. To further examine wind turbine control and to investigate wind turbine operation in combination with other renewable sources recently a Laboratory for renewable energy sources (LARES) has been developed at the Department of Control and Computer Engineering. The Laboratory is in fact a micro grid consisting of: (i) wind turbine set-up placed in an air chamber and driven by powerful blower, (ii) hydrogen fuel cells stack with metal hydride storage supplied by an electrolyser [18-21] and (iii) an array of solar panels placed on the building's roof. The principle scheme of the Laboratory for the renewable energy sources is shown in figure 1. The Laboratory layout is shown in figure 2.

In the following sections Laboratory subsystems are described in more detail.

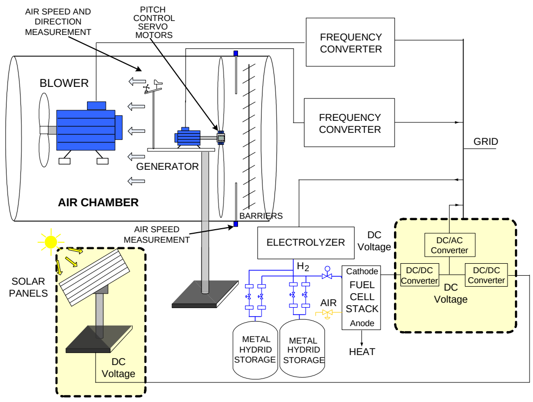

Fig. 1: Principle scheme of the Laboratory for renewable energy sources

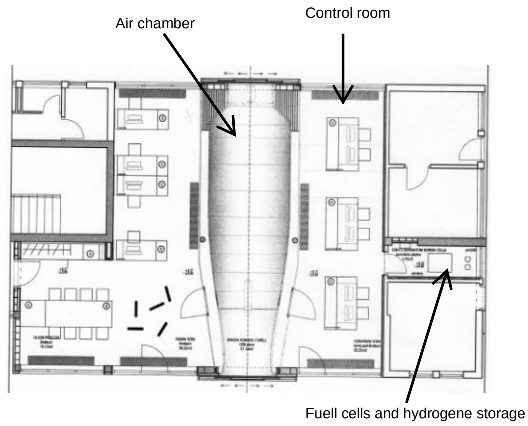

Fig. 2: Layout of the the Laboratory for renewable energy sources.

2. Wind turbine and wind chamber

Wind turbine set-up plays the central role and its development was by far the most challenging task during Laboratory construction. One of the most demanding tasks was the preservation of aerodynamic relations present at MW scale wind turbines. This was addressed by extensive CFD analysis that enabled optimization of the air chamber layout.

The basic postulates during test section design were:

- Preservation of Betz assumption regarding energy transformation (Fig. 3.)

$$v_2 = \frac{1}{3} v_1$$

- Fulfilling of similarity condition:

  o dynamic $\frac{F_{1p}}{F_{1m}} = \frac{F_{2p}}{F_{2m}} = ... = konst = \delta_F$

  o kinematic

  $$\frac{U_{1p}}{U_{1m}} = \frac{w_{1p}}{w_{1m}} = \frac{c_{1p}}{c_{1m}} = ... = konst = \delta_c$$

  o geometry

  $$\frac{D_{2p}}{D_{2m}} = \frac{D_{1p}}{D_{1m}} = \frac{L_p}{L_m} = ... = konst = \delta_L \text{ and}$$

  $\beta_{1p} = \beta_{1m} = \beta_1$

- Respecting of optimal tip-speed ratio for three bladed rotor (Fig. 4.).

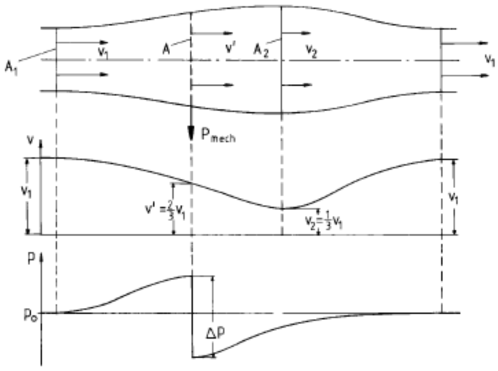

Fig. 3: Wind chamber velocity diagram.

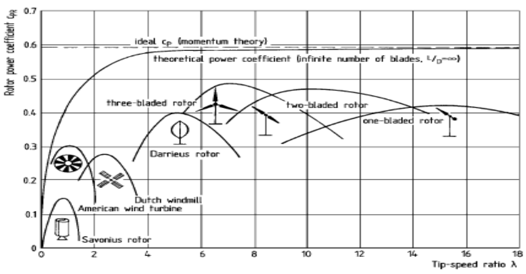

Fig. 4: Rotor tip speed and power diagram.

Geometry of the test section is developed using CFD simulations with intention to obtain the best geometry, which keeps stable boundary layer as thin as possible without recirculating flow. Final design is presented on the pictures.

The test section consist of air inlet, with wind turbine situated in throat (Fig 5., Fig.6.), diffuser, cylindrical portion and portion with reduction of area toward air outlet, where the fan is located.

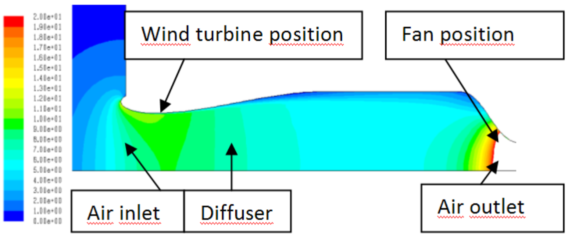

Fig. 5: Velocities distribution (0-20 m/s)

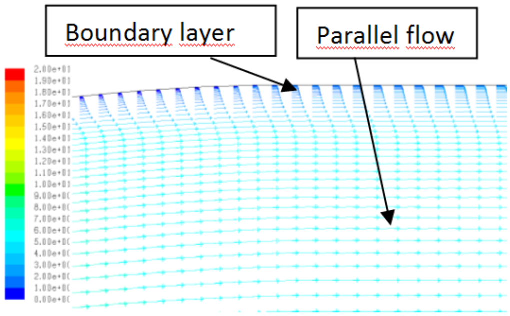

Fig. 6: Velocities vectors magnitude.

Wind chamber layout with wind turbine in it is shown in figure 7.

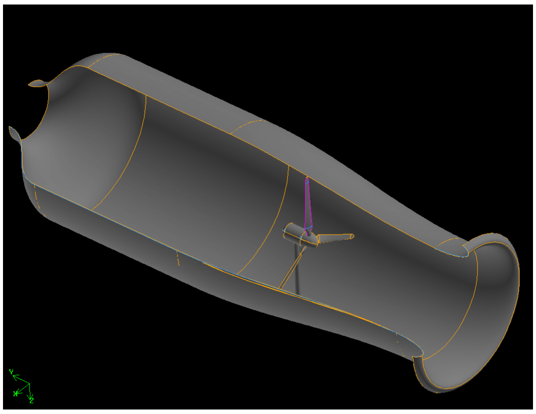

Fig. 7: Wind chamber layout.

Another great challenge was to implement all control functions present on pitch controlled variable speed wind turbines (PCVS) in MW scale. Due to this demand no commercial small wind turbine could be used but completely new design was developed that included pitch actuators and 4Q frequency inverter for grid connection. Significant effort was needed to fit servo motors, gearboxes and pitch controller in very limited space of laboratory turbine's hub. Obtaining realistic flexible tower model with low modal frequencies was another big challenge since this demand compromises tower structural stability. The solution was found in a form of stiff tower mounted on an oscillatory bed and connected to the rigid structure with replaceable springs and dampers.

The implemented wind turbine in the chamber is shown in figure 8.

Fig. 8: Wind turbine in the chamber.

3. Hydrogen fuel cell stack

The hydrogen fuel cells based part of the Laboratory for renewable energy sources is designed for hydrogen production, hydrogen storage and for conversion of the hydrogen energy to electric and thermal energy using fuel cell stack. The hydrogen plant consist of several base devices, such as: electrolyser, metal hydride hydrogen storage tanks, fuel cell stack, voltage converters and cooling system. In addition, plant is equipped with appropriate measuring control and safety devices. The structural scheme of the hydrogen plant is shown in Fig. 9.

Hydrogen unit of the LARES is designed in order to provide hydrogen production by Hogen GC 600 electrolyser, using available electric energy and hydrogen storage in metal hydride containers with 900 s/l storage capacity. The metal hydride containers are characterized by storage of the same quantity of the hydrogen at the considerable lower pressure and volume in comparison with conventional containers. The hydrogen containers are connected with the fuel cell stack through the on/off and control valves, as well as pressure and flow measuring devices. The air with controlled pressure and flow is also conducted to the fuel cell stack in order to produce electric and thermal energy in reaction with hydrogen. The hydrogen unit uses the self-humidified fuel cell stack FCS6432 from the BCS Inc. The used fuel cell stack belongs to the Proton Exchange Membrane (PEM) fuel cell stack class with maximal electric power of 500W and operating temperature of 65 °C. Cooling circuit is based on liquid cooling system which allows the thermal energy measurement necessary for experiment related to cogeneration based exploitation of the unit. Fuel cell stack output voltage is in range from 18V to 30V, so the voltage is converted to 48V voltage of the DC bus by DC/DC boost converter. The electric energy from the DC bus could be transfer to the power grid by DC/AC converter. DC bus could be equipped by super capacitors and batteries. The part of the hydrogen unit is shown in Fig 10.

The used fuel cell needs the hydrogen purity of the class 4 and air purity of the laboratory air class. Hydrogen circuit in the fuel cell is designed as dead

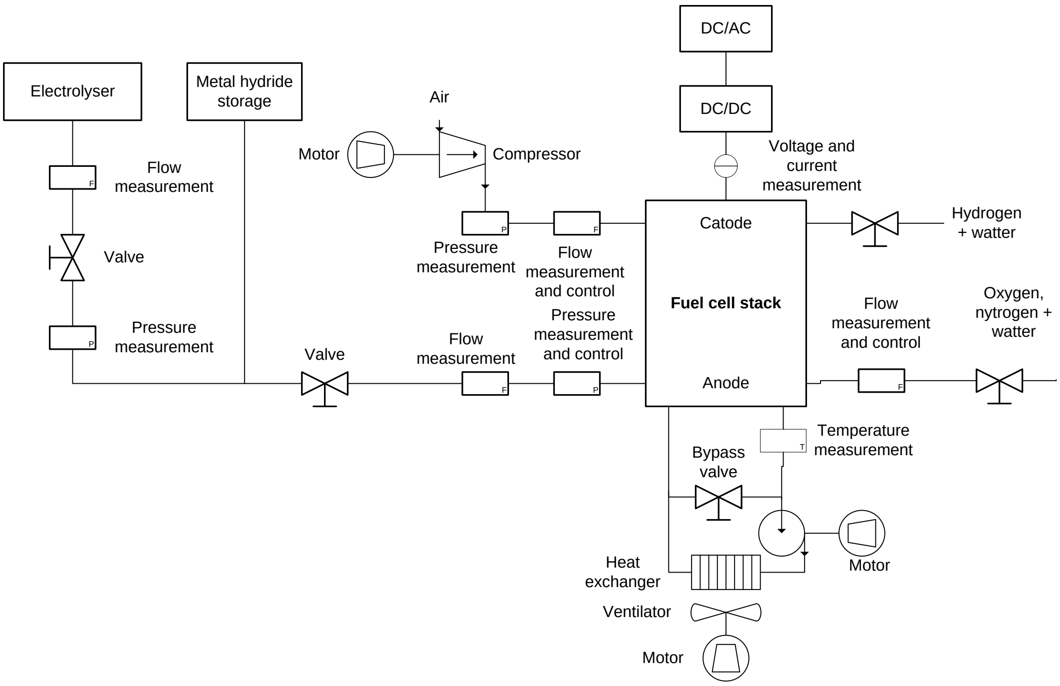

Fig. 9: Structural scheme of the hydrogen plant

ended circuit with periodic hydrogen release and air circuit is closed by control valve in order to control air flow and pressure in the stack. In order to accomplish the identification of the fuel cell stack parameters the fast response control valves are used in both hydrogen and air lines as well as mass flow measurement units for flow measurement. The response time of the valves is under the 20 ms in order to allow action in time range relevant to fuel stack time responses. In comparison with commercial fuel cell stack exploitation elements, the elements used in laboratory hydrogen unit are considerably faster in order to allow excitations and measurement necessary for identification purposes as well as the precise mathematical model obtaining.

Fig. 10: Part of the hydrogen unit placement.

4. Solar PV array

In order to have possibility to perform development in field of microgrid and virtual power plant, it is planned to integrate a photovoltaic system in it. The microgrid based on hydrogen, wind and sun power plant is assigned for experimental research of the control paradigms needed for its optimal synergy with other microgrid parts in order to reach certain objectives on a microgrid level (e.g. maximum efficiency, maximum components lifetime, maximum profit). So far achieved solar energy research results within LARES are in ground solar irradiance modeling based on meteorological inputs, as well as time and geographical data of the location. Developed model was tested against METSTAT model, designed by NREL, which was used in the US National Solar Radiation Database creation. Comparison of our model and METSTAT model is shown in Fig. 11. Improvements are seen in lower RMSE and MBE values and tight grouping of modeled and measured data around ideal curve.

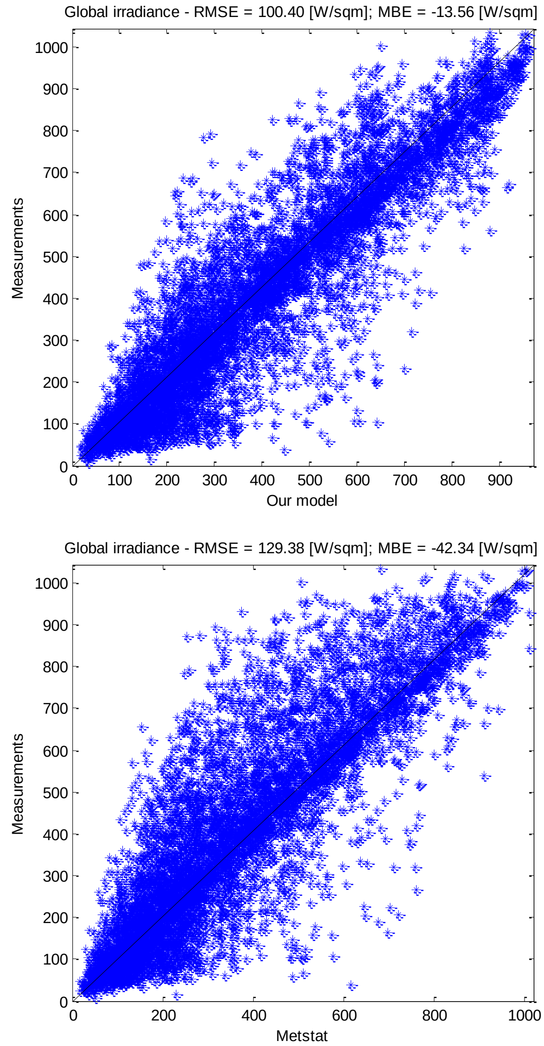

Fig. 11: Our model and METSTAT model global irradiance comparison

It is planned to build a 15 kW PV system with a raw block scheme shown in Fig. 12 . PV panels will be placed on the flat roof of the 50m-high FER skyscraper in two groups. Arrays A1 and B1 will be mounted on fixed surfaces and arrays A2 and B2 on tracking devices to track Sun position on real time basis. This system will incorporate possibility to operate as a standalone entity in Laboratory microgrid and as a grid connected system.

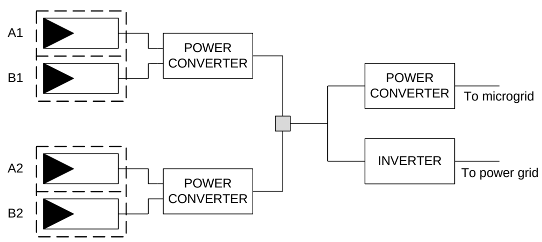

Fig. 12. Block scheme of PV system

5. Control system

The control system for wind power plant is based on National instruments LabVIEW (Laboratory Virtual Instrumentation Engineering Workbench) control platform. All control computational tasks are performed on PC computer. On the other hand, the measurement of the system variables and relevant control signal generation is obtained by specialized input output PXI and cRIO circuits. The principle control scheme of the wind power plant is shown in Fig. 13.

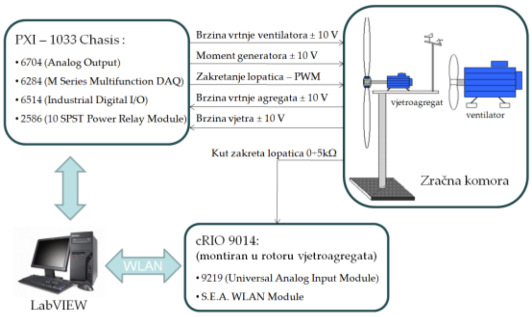

Fig. 13: The basic control scheme of the wind power plant

The equipment for signal measurement and generation could be divided in two groups. The first group contains the NI PXI-1033chassis used for communication between PC computer and input/output modules. Inside the chassis are following modules:

- Analog output module PXI-6704 used for defining the fan reference speed and generator electromagnetic torque,
- Multifunctional analog module PXI-6284 – used as input module for signals of generator rotation speed, rotor position, wind speed etc, and generating the three PWM (Pulse Width Modulation) signals for blades pitch control,
- Digital Input/Output module PXI-6514 used for digital signals in the process,
- Relay module PXI-2586 used for generating the control signals for fan and generator start.

The second group of equipment is used for blade pitch angle measurement. Keeping in mind that the blades are positioned on the rotating part of the wind power plant, the pitch angle measurement and information sending to the PC computer should be provided in the special way in order to avoid the noise caused by sliding rings. In this purpose the NI cRIO 9014 controller is used for blade pitch angle measurement using potentiometers placed in blades bases and for sending the measured data to the PC using WLAN protocol. For obtaining the WLAN functionality the S.E.A WLAN module is used.

Control system for hydrogen power plant is also based on NI equipment. All computational tasks related to control of the hydrogen unit are accomplished by controller unit based on National instrument cRIO-9024 controller with appropriate input and output devices. The controller is based on processor unit with 800MHz clock, 512MB RAM and 4GB of the permanent memory. The cRIO micro controller executes in real time all control algorithms related to fuel cell, temperature and voltage converter control. In addition cRIO controls the ambient air exchange in hydrogen unit chamber as well as the ambient temperature. The safety functions related to the fire and explosion prevention are accomplished by parallel supervising system based on LOGO PLC which monitors the hydrogen concentration in the hydrogen unit chamber as well as the ventilation function. The safety system provides shut down in case of control system failure.

6. Experimental research

The Laboratory for renewable energy equipped by wind, solar and hydrogen based power plant as well as appropriate HIL (Hardware In the Loop) systems is a good foundation for research and development activities related to separate power plants as well as microgrid and virtual power electric plant related activities.

The specific characteristics of the wind power plant makes possible research in controlled wind conditions as well as research related to reducing of the structural strain by using novel control algorithms [1, 2, 3, 4, 7, 8, 9, 10, 11, 12, 13]. The blade pitch control algorithm based on individual blade control achieves the uniform aerodynamic blades torque in condition of non uniform wind gradient distribution. This approach could decrease plant structural vibrations and increase plant life time.

The design of the hydrogen based power plant with fast response valves makes possible the system identification as well as the control algorithm development [19. 20, 21]. The temperature sensors placed in fuel cell itself and in cooling system are good foundation for temperature characteristic testing as well as cogeneration system investigation. The whole structure of the hydrogen power plant is perfect platform for development of the adaptive, optima and extremal control algorithms [15, 16, 17, 18].

The developed algorithms could be tested on the HIL structure before their usage on the real plant.

The micro grid control algorithm development should be based on multi criteria optimal control algorithms. The control algorithms should take into account the technical, economic and ecologic control criteria. These algorithms should determine the energy flow into micro grid according to available power as well as power demand and energy storage.

7. Conclusion

The result of almost two years of development is a realistic scaled model of MW scale PCVS wind turbine that can be efficiently used to investigate various control algorithms as presented in the paper. Besides control algorithms other aspects of wind turbine operation can be investigated in the Laboratory as well. Wind turbine can be grid connected but can also be used to power the electrolyser thus producing hydrogen needed for later use in fuel cells. This configuration of the system is good foundation for investigation of complex power system control strategies.

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References

1. Jelavić, M., Perić, N.: Wind turbine control for highly turbulent winds Automatika, Journal for Control, Measurement, Electronics, Computing and Communications. 2009, 3-4; p.p. 135-151
2. Vrdoljak, K., Radošević, T., Perić, N.: Identification of Power System Model Parameters for Sliding Mode Based Load-Frequency Control, Proceedings of the International IEEE conference EUROCON 2009., St. Petersburg :, 2009. p.p. 540-547
3. Jelavić, M., Petrović, V., Perić, N.: Individual pitch control of wind turbine based on loads estimation Proceedings of the 34th Annual Conference of the IEEE Industrial Electronics Society (IECON 2008), Orlando, SAD, 2008. p.p. 228-234
4. Petrović, V., Jelavić, M., Perić, N.: Identification of Wind Turbine Model for Individual Pitch Controller Design CD-ROM Proceedings of the 43rd International Universities Power Engineering Conference, Padova, Italija, 2008.
5. Radošević, T., Vrdoljak, K., Perić, N.: Optimal Sliding Mode Controller for Power System's Load-Frequency Control Proceedings of the 43rd International Universities Power Engineering Conference, UPEC 2008
6. Vrdoljak, K., Perić, N., Mehmedović, M.: Optimal Parameters for Sliding Mode Based Load-Frequency Control in Power Systems Proceedings of the 10th International Workshop on Variable Structure Systems, VSS'08., IEEE, 2008. p.p. 331-336.
7. Jelavić, M., Perić, N., Petrović, I.: Damping of Wind Turbine Tower Oscillations through Rotor Speed Control CD-ROM Proceedings of the Ecologic Vehicles and Renewable Energies International Exhibition and Conference - EVER 2007., Monako, 2007.
8. Vrdoljak, K., Perić, N., Petrović, I.: Estimation and Prediction in Load-frequency Control, Proceedings of the International Conference on Power Engineering, Energy and Electrical Drives, POWERENG 2007., Setubal, 2007. p.p. 785-790.
9. Vrdoljak, K., Težak, V., Perić, N.: A Sliding Surface Design for Robust Load-frequency Control in Power Systems, Proceedings of the Power Tech 2007., Lausanne, , 2007.
10. Jelavić, M., Perić, N., Petrović, I.: Identification of Wind Turbine Model for Controller Design, Preoceedings of the 12th International Power Electronics and Motion Control Conference, Portorož, 2006. p.p. 1608-1613
11. Vašak, M., Klanjčić, D., Perić, N.: Piecewise Affine Identification of MIMO Processes, Proceedings of the 2006 IEEE International Conference on Control Applications, Omnipress, 2006. p.p. 1493-1498
12. Vrdoljak, K., Petrović, I., Perić, N.: Discrete-Time Sliding Mode Control of Load Frequency in Power Systems with Input Delay, Proceedings of the 12th International Power Electronics and Motion Control Conference, Portorož, 2006. p.p. 567-572
13. Bago, M., Marijan, S., Perić, N.: Core development for CANopen minimum slave in distributed control systems, Proceedings of International Conference on ELECTRICAL DRIVES and POWER ELECTRONICS EDPE 2005, Zagreb, 2005.
14. Jelavić, M., Perić, N., Car, S.: Estimation of Wind Turbulence Model Parameters, Proceedings of the 2005 International Conference on Control and Automation, 2005. p.p. 89-94
15. Ban, Ž., Bjažić, T., Volarić, I.: Voltage Control of a DC/DC Boost Converter Powered by Fuel Cell Stack, Proceedings of 32nd International Convention on Information and Communication Technology, Electronics and Microelectronics - Computers in Technical Systems (CTS), Opatija, 2009. p.p. 82-87
16. Bjažić, T., Pavlović, T., Ban, Ž.: Estimation of Boost Converter State-Space Variables using Fast Output Sampling Method, Proceedings of 15th International Conference on Electrical Drives and Power Electronics, Dubrovnik, 2009. p.p. 1-6
17. Pavlović, T., Bjažić, T., Ban, Ž.: Control of a Standalone DC Voltage Source with Fuel Cell

Stack, Proceedings of 32nd International Convention on Information and Communication Technology, Electronics and Microelectronics - Computers in Technical Systems (CTS), Opatija, 2009. p.p. 88-91

18. Bjažić, T., Ban, Ž.: Temperature Control System of the PEM Fuel Cell Stack, Proceedings of the Croatian Society for Information and Communication Technology, Electronics and Microelectronics - MIPRO, Opatija, 2008. p.p. 37-42
19. Bjažić, T., Ban, Ž., Pavlović, T.: Power Control of the PEM Fuel Cell System Using Gain-Scheduling Controller, Proceedings of the MIPRO2008 , Computers in Technical Systems, Opatija, 2008. p.p.43-48
20. Bjažić, T., Ban, Ž., Volarić, I.: Control of a Fuel Cell Stack Loaded with DC/DC Boost Converter, Proceedings of the 2008 IEEE International Symposium on Industrial Electronics, Cambridge, 2008. p.p. 1489-1494
21. Bjažić, T., Ban, Ž., Perković Franjić, M.: Linear Model of PEM Fuel Cell Power System for Controller Design Purposes, Proceedings of the MIPRO 2007 : 30th Jubilee International Convention : Computers in Technical Systems, Opatija, 2007. p.p. 46-51