

In the case of overload or wind speed decreasing, the output voltage of the DC-DC converter starts to decrease too. The fuel cell output is stabilized to a lower voltage level ($V_{d,r} - \Delta V$). Both power sources are connected to DC bus through diodes [30], because of the diode included in fuel cell module; therefore, the bigger voltage (wind) provides the power in the intervals 1 and 2 (Fig. 5) and both power sources are providing power in the interval 3. These intervals are continuously changing in accordance with the speed of the wind [30].

The load current in the interval 3 is equal to:

$$I_{\text{load}} = I_{\text{dcdc}} + I_{\text{f.c.}} \text{ (A)}, \quad (3)$$

where I_{load} – load current, A;

I_{dcdc} – DC-DC converter current, A;

$I_{\text{f.c.}}$ – fuel cell current, A.

B. Analysis of the Hydrogen Energy Storage Operation

The rated amount of hydrogen in the tank is:

$$n_{\text{H}_2, \text{rated}} = \frac{p_{\text{H}_2} \cdot V_t}{R \cdot T} \text{ (mol)}, \quad (4)$$

where p_{H_2} – hydrogen pressure in the tank, Pa;

V_t – tank volume, m³;

$R = 8.31 \text{ J/(mol} \cdot \text{K)}$ – gas constant;

T – absolute temperature, K.

The dependency of the hydrogen amount in the tank on the tank volume and gas pressure is presented in Fig. 6. For the tank used in the experiments, the rated amount of hydrogen at the initial pressure 20 MPa is equal to 403 mol. According to Table I, the consumption of the hydrogen by the fuel cell is equal to:

$$V'_{\text{H}_2} = \frac{V'_{\text{H}_2, \text{rated}}}{P_{\text{f.c., rated}}} \cdot P_{\text{f.c.}} \text{ [l/min]}, \quad (5)$$

where V'_{H_2} – hydrogen consumption by the fuel cell at atmospheric pressure, l/min;

$V'_{\text{H}_2, \text{rated}}$ – hydrogen consumption by the fuel cell at the rated power and atmospheric pressure, l/min;

$P_{\text{f.c., rated}}$ – rated power of the fuel cell, W;

$P_{\text{f.c.}}$ – used power of the fuel cell, W.

For the mentioned fuel cell, hydrogen consumption is:

$$V'_{\text{H}_2} = \frac{130}{8500} \cdot P_{\text{f.c.}} = 0.0153 \cdot P_{\text{f.c.}} \text{ (l/min)}. \quad (6)$$

The consumption of hydrogen in mol/s is:

$$n'_{\text{H}_2} = \frac{p_{\text{atm}} \cdot V'_{\text{H}_2}}{R \cdot T \cdot 60 \cdot 1000} \text{ (mol/s)}, \quad (7)$$

where p_{atm} – atmospheric pressure, Pa.

For the mentioned fuel cell, the consumption of hydrogen is $1.03 \cdot 10^{-5} \cdot P_{\text{f.c.}}$ mol/s. The possible usage time of the stored hydrogen amount is:

$$t = \frac{n_{\text{H}_2, \text{av}}}{n'_{\text{H}_2}} = \frac{n_{\text{H}_2, \text{rated}} - n_{\text{H}_2, \text{min}}}{n'_{\text{H}_2}} \text{ (s)}, \quad (8)$$

where $n_{\text{H}_2, \text{min}}$ should be calculated according to the fuel cell operation pressure and tank volume:

$$n_{\text{H}_2, \text{min}} = \frac{p_{\text{H}_2, \text{min}} \cdot V_t}{R \cdot T} \text{ (mol)}, \quad (9)$$

where $p_{\text{H}_2, \text{min}}$ – minimum fuel cell operation pressure, Pa.

For the mentioned fuel cell and tank at $p_{\text{H}_2, \text{min}} = 515 \text{ kPa}$ and $V_t = 0.05 \text{ m}^3$, the unused amount of hydrogen $n_{\text{H}_2, \text{min}}$ is 11 mols, i.e., 2.73 % of the rated amount. The electrolyser was not applied in this work. The possible usage time of the stored hydrogen depends on the available amount of hydrogen and the consumption of the hydrogen by the fuel cell, which is the function from the used fuel cell power, as it is presented in Fig. 7.

V. EXPERIMENTAL RESULTS

In the experiment, the wind generator was replaced with a DC power source (Fig. 8). The fuel cell was connected to the DC bus only through the diode without the step-up converter; therefore, the 40 V rated DC bus voltage was accepted. The experimental results (Fig. 9) confirm the theoretical method (Fig. 5) described in [30].

When the output voltage of the DC-DC converter is less than the voltage of the fuel cell, the DC bus voltage V_d (Fig. 9.b) is equal to fuel cell voltage and the load current I_{load} is equal to fuel cell current $I_{\text{f.c.}}$. The increase in the DC-DC converter output voltage was made by increasing the duty ratio of the power switch Q2 (Fig. 3). The duty ratio of the switch Q1 is 100 %, because of the 30 V DC input voltage and step-up operation mode chosen for the experiment. Increasing the DC-DC converter output voltage, the current I_{dcdc} and DC bus voltage V_d increases till V_d reaches the rated value.

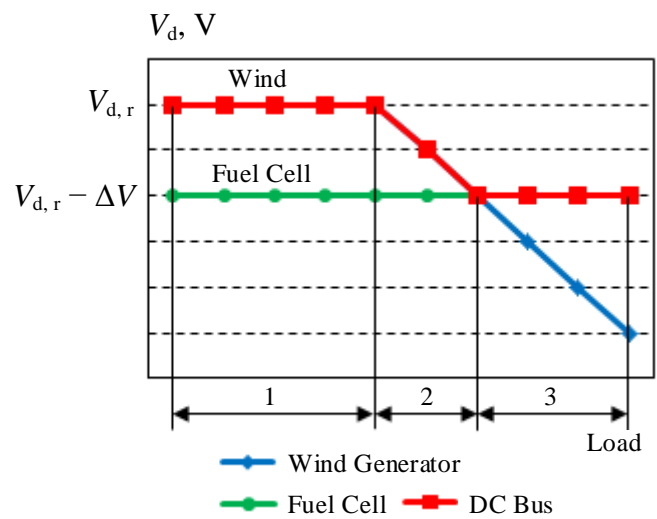


Fig. 5. The voltage/load characteristics of the alternative energetics microgrid: V_d – DC bus voltage; $V_{d,r}$ – DC bus rated voltage.

The form of the current is very important for the fuel cell. When the load is powered only by the fuel cell, the form of current is smooth (Fig. 10). In the case when the load is powered partially by DC-DC converter and partially by the fuel cell, a filter is required. The diagrams of the current without a filter are presented in Figs 11–12.

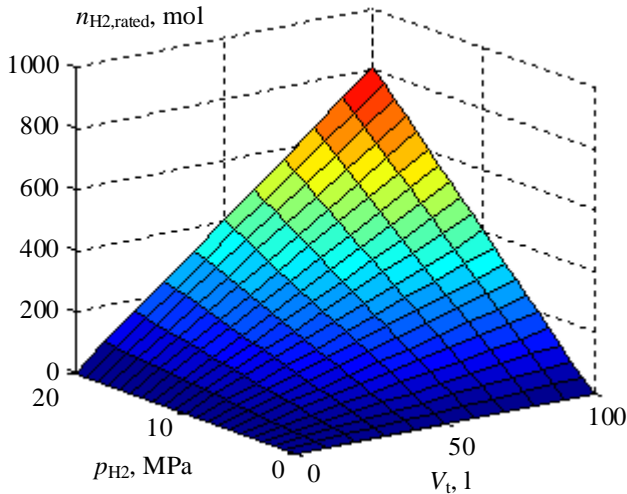


Fig. 6. Amount of hydrogen in a tank depending on the volume of the tank and the pressure of hydrogen.

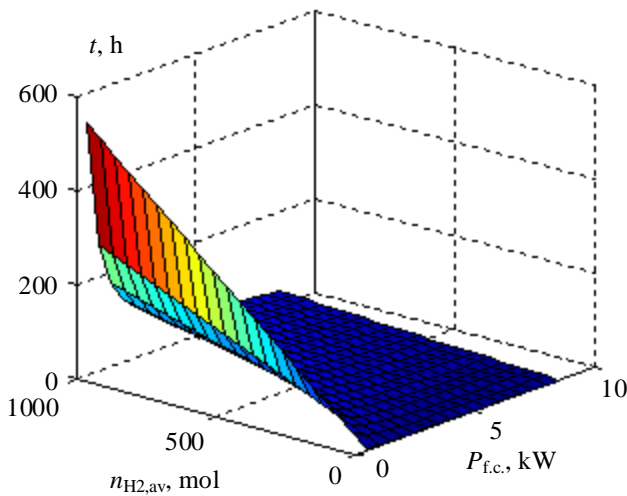


Fig. 7. Possible usage time in hours of the stored hydrogen depending on the used power of the fuel cell and the available hydrogen amount.

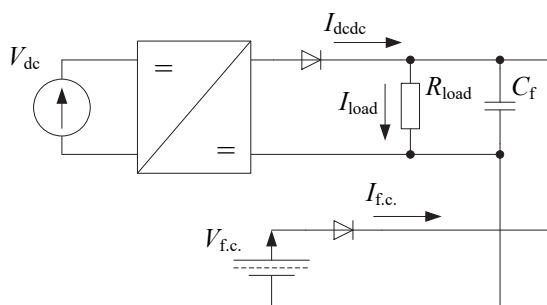


Fig. 8. The simplified principal scheme of the experiment.

The experiments demonstrated that the pulsations of the current are caused by the DC-DC converter that operates in PWM mode. The pulsations increase in this case by decreasing the current of the fuel cell. The usage of the 450 μF capacitor can improve the form of the current at the 39 Ω load (Figs 13–14). The capacity of the filter was selected experimentally, and its calculation is the aim of our future work.

VI. CONCLUSION

According to the strategic objectives of the use of renewable energy resources, the alternative energetics microgrid based on the wind energy was used in this research with the aim to develop the solutions for effective use of the renewable energy resources (wind generators in particular) in alternative energetics devices, at the same time providing an uninterrupted power supply of the critical loads.

After the analysis of the possible configurations of the microgrid, the DC coupling was chosen, because there are advantages corresponding to renewable energy sources and energy storage systems. The autonomous operation mode of the microgrid was chosen, which means that the conventional power grid is not applied, and in the case of low wind power, the energy storage system is necessary for providing an uninterrupted power supply. The experimental results demonstrate that the hydrogen energy storage system provides an uninterrupted power supply in the alternative energetics microgrid based on wind energy. In the case when the wind generator speed is low, the necessary power is provided by the fuel cell.

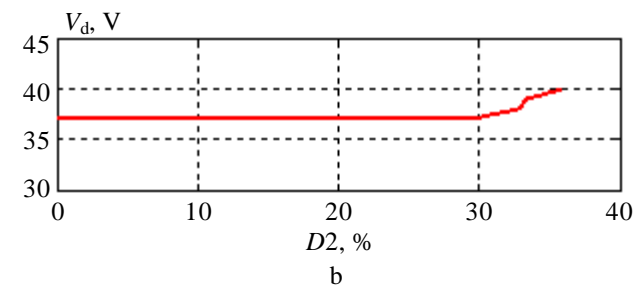
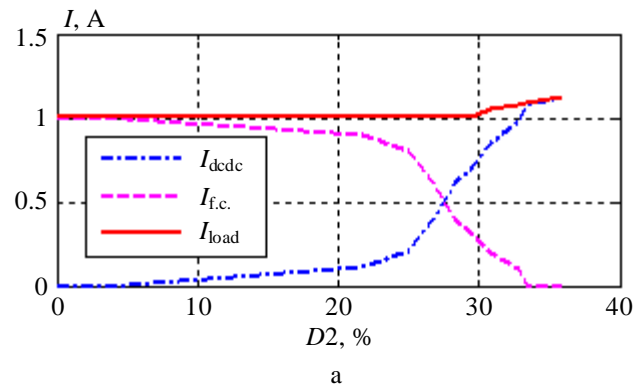


Fig. 9. Currents (a) and DC bus voltage (b) depending on the DC-DC converter duty ratio $D2$ in the boost mode at the 30 V DC converter's input voltage.

If the wind speed and, the wind generator output power is sufficient, the fuel cell must be in the “run” mode all the time, because the transition from stand-by mode to run (power ready) mode can require up to 5 seconds [31], [32].

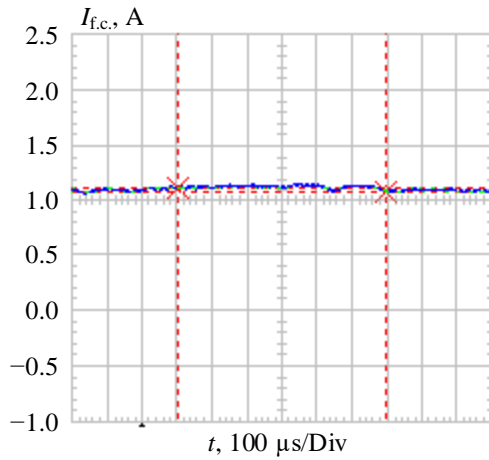


Fig. 10. Current of the fuel cell in the case when load is powered only by the fuel cell.

Theoretical analysis of the microgrid operation with the hydrogen energy storage system includes the calculation of the hydrogen consumption and the possible usage time of the stored hydrogen in the case when the tank is applied instead of the electrolyser. The possible usage time of the stored hydrogen depends on the available amount of hydrogen and the consumption of hydrogen by the fuel cell, which is the function from the used fuel cell power.

The hydrogen consumption was calculated for the full-scale system, but the precision of the hydrogen pressure measurement device was not enough for a small-scale experiment at small duration and power; therefore, there is no experimental data about hydrogen consumption.

The experimental results demonstrated that if the wind generator can provide only a part of the needed power, the abiding power can be provided by the fuel cell. In this case, a load filter is necessary to decrease the fuel cell current pulsations. When the output voltage of the DC-DC converter is less than the fuel cell voltage, the DC bus voltage is equal to the fuel cell voltage and the load current is equal to the fuel cell current.

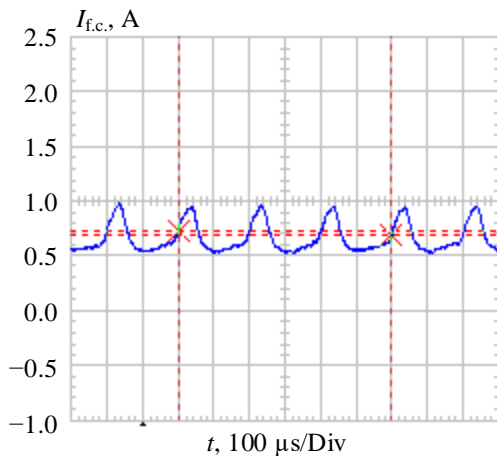


Fig. 11. Current of the fuel cell with rms 0.66 A in the case when load is partially powered by the fuel cell without a load filter.

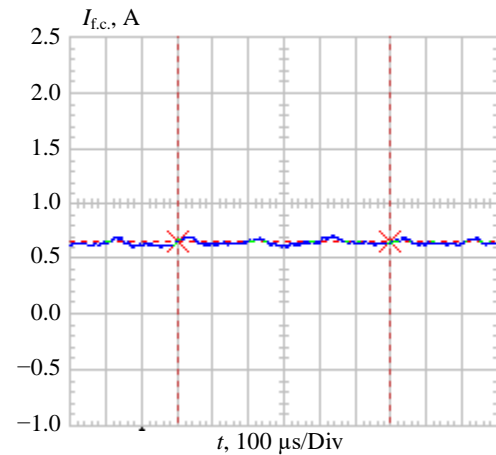


Fig. 13. Current of the fuel cell with rms 0.65 A in the case when load is partially powered by the fuel cell with a load filter.

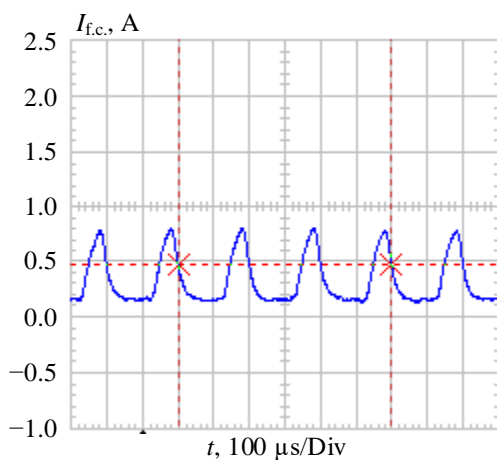


Fig. 12. Current of the fuel cell with rms 0.32 A in the case when load is partially powered by the fuel cell without a load filter.

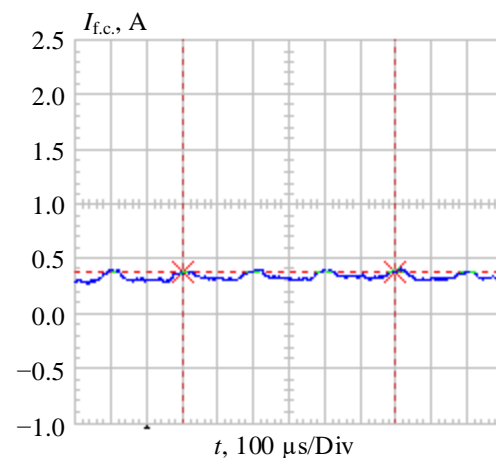


Fig. 14. Current of the fuel cell with rms 0.32 A in the case when load is partially powered by the fuel cell with a load filter.

Increasing the DC-DC converter output voltage, the converter's current and DC bus voltage increases till DC bus voltage reaches the rated value. When the load is powered only by the fuel cell, the form of the current is smooth. In the case when the load is powered partially by DC-DC converter and partially by the fuel cell, a filter is required to prevent undesirable pulsations.

ACKNOWLEDGMENT

This work has been supported by the Latvian National Research program LATENERGI.

REFERENCES

- [1] Latvijas Republikas Vides aizsardzības un reģionālās attīstības Ministrija, "Atjaunojamo energoresursu izmantošanas pamatnostādnes 2006.–2013. gadam (informatīva daļa)," Rīga, 2006.
- [2] A. Adamovičs, V. Dubrovskis, I. Plūme, Ā. Jansons, D. Lazdiņa and A. Lazdiņš, *Biomassas izmantošanas ilgtspējības kritēriju pielietošana un pasākumu izstrāde*, Rīga, 2009.
- [3] K. Bunker, S. Doig, K. Hawley, and J. Morris, "Renewable Microgrids: Profiles From Islands and Remote Communities Across the Globe," 2015.
- [4] The Microgrids Group at Berkeley Lab, "About Microgrids." [Online]. Available: <https://building-microgrid.lbl.gov/about-microgrids-0>.
- [5] H. S. Kumar, "Smart microgrid." 2015.
- [6] The Microgrids Group at Berkeley Lab, "Microgrid Definitions." [Online]. Available: <https://building-microgrid.lbl.gov/about-microgrids-0>.
- [7] T. Roughan, "Workshop on Microgrid Technologies and Applications," *RPI Cent. Futur. Energy Syst. Overv.*, p. 11, 2013.
- [8] R. W. De Doncker, "Future DC Grid Technology for more Decentralized Power Production and Renewable Power Supplies," *IEEE PEDG2012*, 2012.
- [9] A. Graillot, "Hybrid Micro Grids for rural electrification: Developing Appropriate Technology," presented at *AIE Event*, Maputo, 2009.
- [10] A. Suzdalenko, "Research and Development of Control Means for Intelligent Household Electrical Grids," Ph.D. Thesis, Riga Technical University, 2013.
- [11] "MED-Solar Training Course. Module 2. Microgrid Elements," *Universitat Politècnica de Catalunya*, p. 59.
- [12] R. Villafañila Robles, "Microgrids and emulation of distribution energy resources," p. 13.
- [13] P. Karlsson, "DC Distributed Power Systems," Ph.D. Thesis, Lund University, 2002.
- [14] D. Deaconu, A. Chirila, M. Albu and L. Toma, "Studies on a LV DC network," in *2007 European Conference on Power Electronics and Applications*, 2007, pp. 1–7. <https://doi.org/10.1109/EPE.2007.4417634>
- [15] A. Sannino, G. Postiglione and M. H. J. Bollen, "Feasibility of a DC network for commercial facilities," *IEEE Trans. Ind. Appl.*, vol. 39, no. 5, pp. 1499–1507, 2003. <https://doi.org/10.1109/TIA.2003.816517>
- [16] D. J. Hammerstrom, "AC versus DC distribution systems-did we get it right?," in *2007 IEEE Power Eng. Soc. Gen. Meet. PES*, Tampa, FL, pp. 1–5, 2007. <https://doi.org/10.1109/PES.2007.386130>
- [17] A. Kwasinski, "Micro-grids architectures, stability and protections," 2012.
- [18] S. Rolland and G. Glania, "Hybrid Mini-Grids for Rural Electrification: Lessons Learned," CA: Renewable Energy House, Brussels, 2011, 72 p.
- [19] A. Senfelds, M. Vorobjovs, D. Meike and O. Bormanis, "Power Smoothing Approach within Industrial DC Microgrid with Supercapacitor Storage for Robotic Manufacturing Application," in *2015 IEEE Int. Conf. on Automation Science and Eng. (CASE)*, Gothenburg, 2015, vol. 1020, pp. 1333–1338. <https://doi.org/10.1109/CoASE.2015.7294283>
- [20] National Renewable Energy Laboratory, "Power Purchase Agreement Checklist for State and Local Governments," Golden, Colorado, 2009.
- [21] M. A. Maehlum, "What's the Difference Between Net Metering and Feed-In Tariffs?," *Energy Informative*, 2014. [Online]. Available: <http://energyinformative.org/net-metering-feed-in-tariffs-difference>
- [22] G. Zaleskis and I. Rankis, "Problem of an Estimation of the Wind Generators Economic Efficiency in Latvia," in *Proceedings of the 20th International Conference ELECTRONICS 2016*, Palanga, Lithuania, 2016, pp. 16–21.
- [23] E. H. Camm, M. R. Behnke, O. Bolado et al., "Characteristics of Wind Turbine Generators for Wind Power Plants," in *2009 IEEE Power & Energy Society General Meeting*, Calgary, AB, 2009, pp. 1–5. <https://doi.org/10.1109/pes.2009.5275330>
- [24] P. Suskis, "DC/DC Voltage H-Bridge Converter with Fuzzy Logic Control for Autonomous Power Supply," in *54th Int. Scientific Conf. of Riga Technical University*, Riga, Latvia, 2013.
- [25] P. Suskis, A. Andreiciks, I. Steiks, O. Krievs and J. Kleperis, "Microgrid for one side wind-and-hydrogen powered generation," *Latvian Journal of Physics and Technical Sciences*, no. 1, pp. 12–20, 2014.
- [26] I. Galkins and O. Tetervenoks, "Efficiency considerations for non-inverting buck-boost converter operating with direct current control," in *2014 16th European Conf. on Power Electronics and Applicat.*, Lappeenranta, 2014, pp. 1–8. <https://doi.org/10.1109/EPE.2014.6911032>
- [27] O. Tetervenoks and I. Galkins, "Considerations on practical implementation of control system for switch mode current regulator," in *2014 14th Biennial Baltic Electronic Conference (BEC)*, Tallinn, 2014, pp. 225–228. <https://doi.org/10.1109/bec.2014.7320597>
- [28] D. Connolly, "A Review of Energy Storage Technologies for the Integration of Fluctuating Renewable Energy," University of Limerick, 2009, 46 p.
- [29] I. Steiks, "Ūdeņraža enerģētiskās iekārtas spēka elektronikas pārveidotāju izstrāde." Promocijas darbs, Rīgas Tehniskā universitāte, Rīga, 2011, 146 p.
- [30] G. Zaleskis, I. Steiks, A. Pumpurs and O. Krievs, "DC-AC Converter for Load Supply in Autonomous Wind-Hydrogen Power System" in *56th Int. Scientific Conf. on Power and Electrical Engineering of Riga Technical University (RTUCON)*, Riga, Latvia, 2015, pp. 169–173. <https://doi.org/10.1109/RTUCON.2015.7343118>
- [31] HyPM® Fuel Cell Power Modules, Hydrogenics, advanced hydrogen solutions. [Online]. Available: www.hydrogenics.com.
- [32] Hy PM XR8 Installation, Operation and Maintenance Manual, Revision 2, DOC. P/N:1035409-02, Hydrogenics, Aug. 2010.



Genadijs Zaleskis, a Ph.D. Student, received the M.Sc. degree in electrical engineering from Riga Technical University in 2011.

In 2010–2011, he was a Laboratory Technician at the Institute of Industrial Electronics and Electrical Engineering of Riga Technical University. Since 2011, he is a Researcher at the Department of Industrial Electronics and Electrical Technologies of Riga Technical University. His main research fields are electrical technologies and automatic control. He is currently an Electrical Engineer at the Latvian

Transmission System Operator "Augstsprieguma tīkls" Ltd. Address: Institute of Industrial Electronics and Electrical Engineering, Riga Technical University, Āzenes iela 12/1, Riga, LV-1048, Latvia.

Phone: +371 28 380 558

E-mail: genadijs.zaleskis@rtu.lv



Ingars Steiks received the degrees of B.Sc., M.Sc., and Dr. sc. ing. in electrical engineering from Riga Technical University in 2004, 2006, and 2011 respectively. At present, I. Steiks is the Leading Researcher, and his main research fields include multilevel DC/AC converters and DC/DC converters for fuel cell applications.

Address: Institute of Industrial Electronics and Electrical Engineering, Riga Technical University, Āzenes iela 12/1, Riga, LV-1048, Latvia.

E-mail: ingars.steiks@rtu.lv