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MICRO-GRID FOR ON-SITE WIND-AND-HYDROGEN POWERED GENERATION

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The authors propose a micro-grid for autonomous wind-and-hydrogen power generation thus replacing such traditional fossil-fuelled equipment as domestic diesel generators, gas micro-turbines, etc. In the proposed micro-grid the excess of electrical energy from a wind turbine is spent on electrolytic production of hydrogen which is then stored under low-pressure in absorbing composite material. The electrolyser has a non-traditional feeding unit and electrode coatings. The proposed DC/DC conversion topologies for different micro-grid nodes are shown to be well-designed. The prototypes elaborated for the converters and hydrogen storage media were tested and have demonstrated a good performance.

Keywords: *wind power, hydrogen, electrolysis, hydrogen storage, metal hydride, zeolite, PEM fuel cells, step-up buck/boost DC/DC converters, multilevel inverters*

1. INTRODUCTION

The most important renewable energy sources on the Earth – the Sun and Wind – are subject to natural fluctuation: wind not always blows evenly and strongly, and the Sun shines only during a day and not intensively enough in the temperate zones. Therefore, it is important to store the energy produced from such renewable sources as the Sun or Wind. For this purpose, hydrogen – as the environment-friendly energy carrier – can be used.

Nowadays, many wind/hydrogen power generation projects have been realized [1-3]. In all of them the power generated by wind turbines is used. In windy weather the turbine works into load directly, but when the wind-generated power exceeds the load demand the excess power is used for electrolytic production of hydrogen, which is then stored as compressed gas (e.g. in cylinder tanks [2-4,5]). When such wind-generated power is unavailable, electricity can be produced by a fuel cell using the stored hydrogen. However, the cost analysis (see, e.g. [4,5]) shows that traditional technologies of electrolysis and hydrogen compression are expensive and imply quite a large self-consumption of energy.

To raise the efficiency of all energy conversion processes in a wind/hydrogen system, the proposed autonomous micro-grid contains an electrolyser with a non-traditional feeding unit and electrode coatings as well as composite materials for low-pressure storage of hydrogen. Particular attention is paid to the DC/DC converter topologies for different nodes of the grid.

2. STRUCTURE AND OPERATION OF THE MICRO-GRID

The proposed autonomous wind/hydrogen micro-grid (Fig. 1) comprises:

- a three-phase wind-driven synchronous generator on permanent magnets with a diode bridge (Fig. 1*a*);
- a step-down (buck) DC/DC converter (Fig. 1*b*) for adjustment of the generated voltage to that on the common DC bus;
- a hydrogen electrolyser fed by DC/DC converter (Fig. 1*c*);
- composite material for low-pressure hydrogen storage (Fig. 1*d*);
- a proton exchange membrane (PEM) fuel cell (Fig. 1*e*);
- a step-up (boost) DC/DC converter (Fig.1*f*) for adjustment of the fuel cell's output voltage to that on the common DC bus;
- a three-phase output inverter (Fig. 1*g*) for feeding voltage to the load.

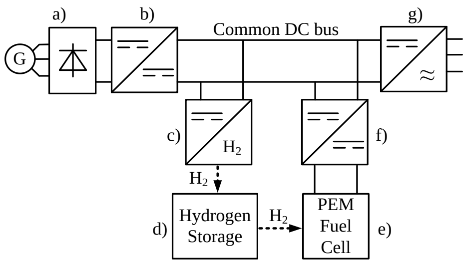


Fig. 1. Block diagram of the proposed autonomous wind/hydrogen micro-grid.

The micro-grid operates in several modes. When the wind-generated energy exceeds the load demand, the excessive electrical energy is converted into chemical energy of hydrogen and accumulated in a storing material. *Vice versa*, when the generated energy is lower than demanded, the fuel cell with an output DC/DC converter takes over the supply function, providing the required energy flow. In the no-demand case, the total wind-generated energy is utilized by the electrolyser and accumulated in the hydrogen storing material.

The micro-grid is designed to ensure a stabilized three-phase AC voltage of 230V. The rated load power of 5 kVA corresponds to that of the generator. A PEM fuel cell HyPM XR8 delivers up to 8.5 kW output power – the short-time maximum load power taken into account in the design of converters. The rated voltage of the DC bus (common for the generator, electrolyser, fuel cell and load inverter) is set to 600 V.

2.1. Generator

The generator employed in the system is a three-phase permanent magnet based synchronous machine equipped with a diode bridge, thus being a variable DC source with the output voltage proportional to the generator`s speed.

2.2. DC/DC Converter

Since the wind energy is subject to natural fluctuation, to maximize the energy yield at low windmill speeds and to adjust the generator's output voltage to the level of DC bus, a DC/DC converter is used.

A transformer-free half-bridge buck-boost DC/DC converter (Fig.2) proposed for the micro-grid consists of a buck shoulder (Fig. 2*a*) and a boost shoulder (Fig. 2*b*) [6,7].

When the converter operates in the step-down mode the circuit matches a classic buck converter with series-connected diode D2 at the output (Fig. 2*a*). Transistor T2 is permanently off, and transistor TR1 is operating in the pulse-width modulation (PWM) mode. In the step-up mode the operation is similar to that of a classic boost converter with parallel diode D1 at the input (Fig. 2*b*). TR1 is permanently in the conduction mode, and TR2 – in the PWM mode.

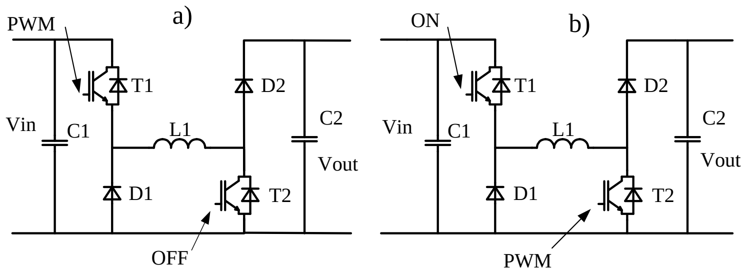


Fig. 2. DC/DC converter circuit: a) classic buck converter with a series-connected diode at the output; b) classic boost converter with a parallel diode at the input.

This topology has the following advantages: simple and cheap design, simple control system, small size, no transformer losses, and ability of the converter to step-up and -down the voltage of the same input-output polarity.

The proposed converter has been verified experimentally on a 5kW prototype. Its efficiency *vs.* output power is shown in Fig.3.

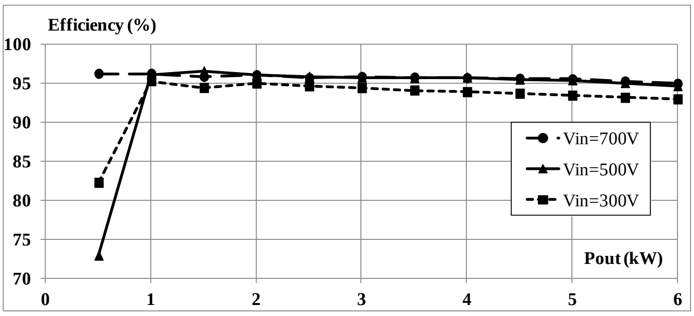


Fig. 3. Efficiency of the proposed converter *vs.* the output power for step-down (V_{in} = 700V) and step-up modes (V_{in} = 300 V, V_{in}=500V).

The experimental results shown in Fig. 3 prove the converter's ability to adjust the output voltage to the level of a common DC bus at the generator's speed exceeding 60 rpm.

3.1. Hydrogen low-pressure storage in composite materials

In chemical reaction between hydrogen and composite material, the hydrides are formed with a heat release (ΔH_f). The larger ΔH_f, the more thermodynamically stable is hydride, and a higher temperature is needed to desorb hydrogen. The desorption temperature in practical applications should be below 100 ^oC, and ΔH_f should not exceed -48 kJ/mol [8]. To determine enthalpy ΔH_f and entropy ΔS_f of hydrogen absorbing material, the van't Hoff equation can be applied:

$$\ln\left(\frac{p_{H_2}}{p^{\Theta}}\right) = \frac{\Delta H^{\Theta}}{RT} - \frac{\Delta S^{\Theta}}{R}, \quad (1)$$

where ΔH^{Θ} and ΔS^{Θ} are changes of standard enthalpy and entropy, p_{H_2} is the measured pressure and p^{Θ} is the thermodynamic reference pressure.

In particular, storing hydrogen in porous media based on a physisorption mechanism is one of the approaches to reach the US Department of Energy target for 2015, namely, 9 wt% of on-board hydrogen storage [8]. The hydrogen storage in zeolites, stable and metastable metal hydrides as well as in different chemical hydrides and composites are being studied for application in vehicles and power supply systems to replace tanks with compressed gas [9].

The developed low-pressure hydrogen storage is based on $LaAl_{0,3}Ni_{4,7}$ alloy composite with porous oxide and has gravimetric hydrogen adsorption capability 1.6 wt%; the total amount of 50 kg allows storing at least 7 Nm^3 of hydrogen gas. The charging pressure is from 2.5 bar up to 15 bar, the temperature <25 ^oC, and the discharge at temperatures above 65 ^oC. The hydrogen sorption experiments for different metal hydride activated porous oxides and zeolites were performed with PCTPro-2000 (*SETARAM*) at 26°C, applying 2.5 bar hydrogen gas pressure (see Fig. 4 where the adsorbed hydrogen (wt%) corresponds to the weight of sample [9-11]).

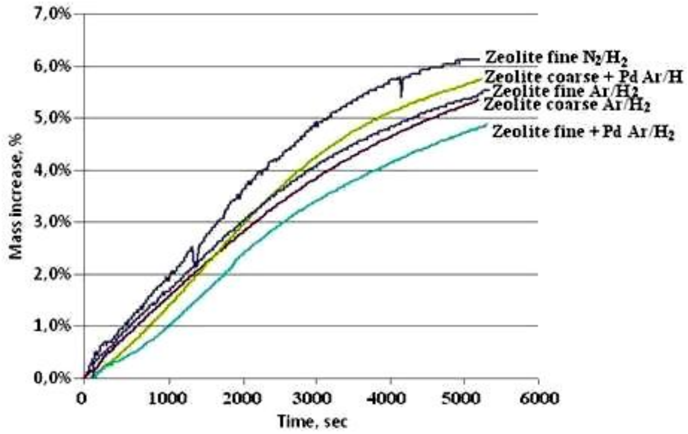


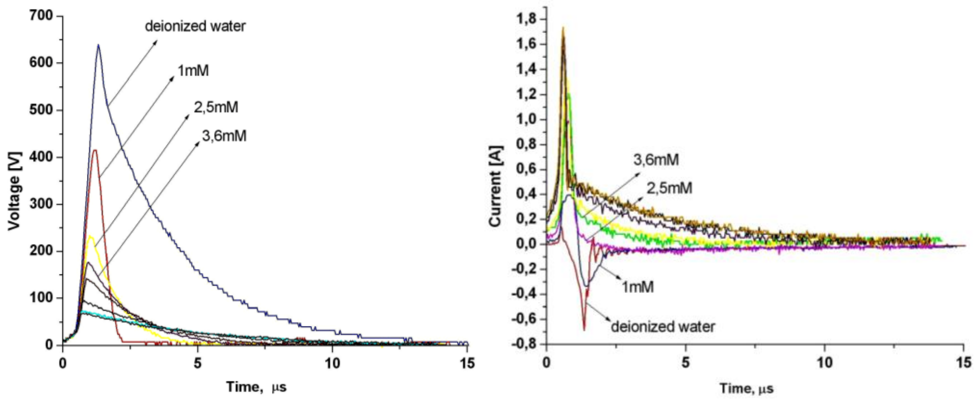
Fig. 4. Hydrogen sorption kinetics of different ion-exchanged zeolites and zeolite/Pd composites (pressure H_2 1 bar, temperature fall from 300 to 26 ^oC).

In Fig. 4 it can be seen that the ammonia-exchanged zeolite sample provides the highest concentration of adsorbed hydrogen: ~ 6 wt%; the zeolite/Pd composites absorb hydrogen slower and in smaller amounts.

3.2. Water electrolysis and its peculiarities

Hydrogen is not available on Earth in a free form; therefore, the cost of its production makes up a major proportion of the ultimate price of hydrogen [12]. This is the main reason for urgent elaboration of effective electrolysis methods. Currently, in the real operating conditions the cycle efficiency does not exceed 50%. Therefore, while DC power is classically used for electrolysis, the pulse mode powering has also been proposed [13].

The developed electrolyser consists of 30 series-connected cells and has the hydrogen production capacity of 0.5 Nm^3/h. The power consumption is up to 3 kW at the maximum voltage of 65 V and amperage of 40 A. When the ~1 mcs high-voltage pulses are applied to a single electrolytic cell, the pulse amplitude is maximal in deionized water (Fig. 5*a*); at increasing concentration of electrolyte (KOH) in the PEM cell the amplitude decreases, while the discharge tail becomes longer.



a) b)

Fig. 5. Inductive voltage pulses (a) and induced current pulses (b) at different concentrations of KOH solution in the water electrolysis cell.

In the measurements it was observed that the current changes its direction from negative to positive as the concentration of electrolyte increases, passing through the point where the current pulse has no long tail (Fig. 5*b*). The energy efficiency (calculated from *V-I* curves of Fig.5) is about 94-97 % [14]. Electrolysis proceeds during the discharge after high-current pulse, and the applied voltage can be expressed as the sum of potentials on both electrodes and its drop on the electrolyte:

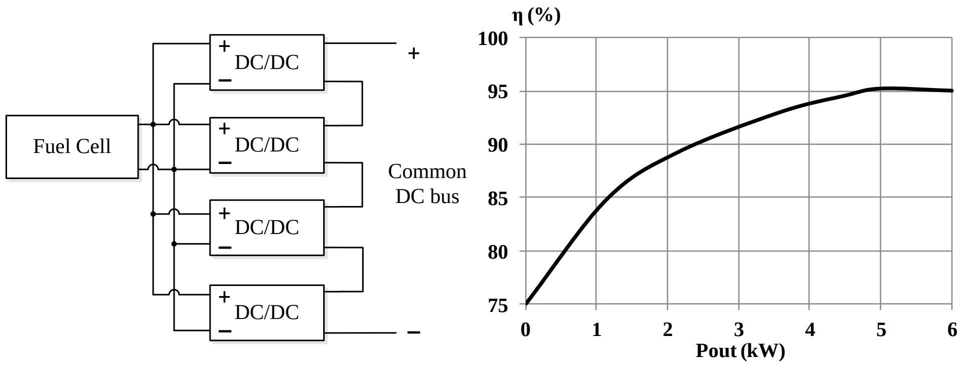
$$E_{appl} = E_e + |\eta_c| + |\eta_a| + IR, \qquad (2)$$

where η_c, η_a are the cathode and anode potentials, respectively, E_e =1.23V is the equilibrium cell voltage for decomposition of water, and *IR* is the heat loss in electrolyte. An alternative way to increase the efficiency of electrolysis is the nanostructuring and modification of the electrode surfaces [15]. It is found that nanostructuring reduces the values of electrode potentials η_c and η_a thus decreasing the applied voltage and heat loss in an electrolysis cell. Plasma-sprayed Ni-Al protective coating of 316L steel anode-cathode electrodes is tested in a long-term (24 h) electrolysis process. It is found that such Ni-Al coating protects both the anode and the cathode from corrosion and reduces the potential of hydrogen evolution. The results obtained show that the coating works best in the case of steel electrodes.

4. DC/DC AND DC/AC CONVERTERS

4.1. DC/DC step-up converter for the fuel cell

Block diagram of the step-up DC/DC converter proposed for the fuel cell is shown in Fig.6a. To increase the overall efficiency of DC/DC conversion the converter is split into several modules connecting the inputs in parallel and outputs – in series. The proposed converter consists of four modules (the double inductor push-pull topology is discussed in more detail in [16, 17]).



a) b)

Fig. 6. The proposed step-up DC/DC converter:
a) structure; b) experimentally measured efficiency *vs*. output power.

Using more modules in the same configuration would increase the overall converter's efficiency slightly more; however, from the price considerations a four-module double inductor conversion (DIC) system is a more reasonable choice. The main advantages of such configuration are:

- reduced power for handling of individual transformers, which results in a smaller size of transformer and its simpler design;
- significantly reduced primary switch conduction losses, which make up the largest proportion of the total conversion losses.

The high overall efficiency at conversion of the fuel cell output voltage is confirmed experimentally (Fig.6*b*).

4.2. DC/AC inverter for load supply

The multilevel inverters make it possible to generate the output voltage waveforms with low harmonic distortion even at low frequency switching, thus significantly decreasing the commutation losses. Among different multilevel topologies for inverters the main three are: the neutral point clamped converter

(NPC), the cascaded H-bridge converter, and the flying capacitor converter [18]. Since a cascaded H-bridge converter requires isolated DC voltage supply for each module while the flying capacitor converter requires more capacitors, the NPC type inverter was chosen for feeding voltage to the load.

Since the step-up DC/DC converter of the fuel cell comprises four series-connected module outputs, a five-level NPC inverter (Fig. 7) was designed and tested. One its phase contains eight controlled switches and twelve diodes (Fig. 7a).

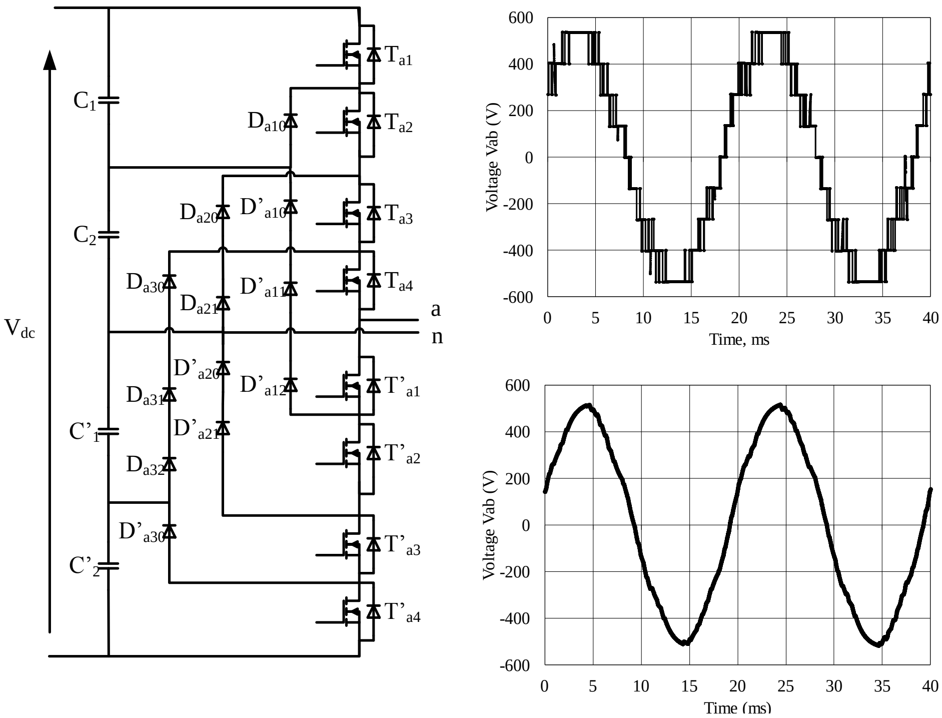


Fig. 7. Five-level NPC inverter: a) one-phase topology; b) output line voltage waveforms without (top) and with (bottom) switching filter

The efficiency of the NPC inverter with output filter is found to be ~95% at the 5kW active load. The total harmonic distortion (THD) of the inverter voltage after the output filter is 3.1 % at the switching frequency of 2.5 kHz.

5. CONCLUSIONS

Based on results of the work the following conclusions can be drawn.

Testing of the proposed wind/hydrogen micro-grid has shown its good performance.

Good results have also been obtained for the proposed non-traditional feeding unit and electrode coatings of the electrolyser. To avoid cracks arising in such a coating when utilized as cathode during a prolonged electrolysis it was proposed to use plasma sprayed Ni-Al coated steel as cathode and anode in the electrolytic cell. The results of testing in a 24-hour electrolytic process show that the Ni-Al coating protects both the anode and cathode from corrosion and reduces the potential of hydrogen evolution.

The porous silica-based materials – raw zeolite or doped with catalyst metal (MH_x; Pd) – used as the storage media have been shown to provide better and safer hydrogen storage as compared with compressed gas in cylinder.

The proposed power converter is simple and adjusts the generator's output voltage to the level of the common DC bus of the micro-grid, ensuring ~95% efficiency at the rated power. The topologies developed for conversion of electrical energy in different nodes of the micro-grid have demonstrated their effectiveness.

The efficiency of the proposed modular step-up DC/DC converter matched with a five-level inverter exceeds 90% at the conversion from fuel cell to load at the rated power, with the output voltage total harmonic distortion being ~ 3%. The common DC bus allows for potential integration with other renewable energy sources or storage media.

ACKNOWLEDGEMENT

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AUTONOMAS VĒJA UN ŪDEŅRAŽA ELEKTROAPGĀDES SISTĒMAS REALIZĀCIJA UN TESTĒŠANA

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K o p s a v i l k u m s

Rakstā piedāvātā mikrotīkla izpēte ir veikta ar mērķi izstrādāt autonomu, uz vēja un ūdeņraža enerģiju balstītu elektroapgādes sistēmu, kas varētu aizvietot tradicionālās fosilā kurināmā sistēmas, piemēram, mājsaimniecību dīzeļa ģeneratorus, gāzes mikroturbīnas u.c. Mikrotīkla elektroapgādes sistēmā vēja agregāta saražotā elektroenerģija tiek pārveidota atbilstoši standarta maiņsprieguma elektroapgādes parametriem un piegādāta slodzei. Pārpalikusī enerģija tiek pārveidota un uzkrāta ūdeņraža formā, izmantojot elektrolīzes iekārtu un kompozītmateriālu uzkrājēju. Ja pieejamā vēja enerģija nenosedz slodzes enerģijas patēriņu, elektroenerģijas padeves funkciju ar atbilstoša energoelektronikas pārveidotāja palīdzību pārņem ūdeņraža degvielas elements. Ja, savukārt, slodzei nav nepieciešama enerģija, no vēja saražoto enerģiju izmanto elektrolīzes iekārta un tā tiek uzkrāta ūdeņraža formā, atbilstoši uzkrājēja ietilpībai.

Piedāvātajā mikrotīklā ir izmantota elektrolīzes iekārta ar netradicionāliem elektrodu pārklājumiem un barošanas bloku, kā arī zemspiediena kompozītmateriālu ūdeņraža uzkrājējs. Galvenie mikrotīkla elektriskās enerģijas pārveidošanas mezgli ir realizēti uz energoefektīvu energoelektronikas pārveidotāju bāzes. Ir izveidoti atsevišķo piedāvātās elektroapgādes sistēmas iekārtu prototipi un veiktas to eksperimantālās pārbaudes, gan atsevišķi, gan darbam kopējā sistēmā.

26.09.2013.