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УДК 620.92

SELF-SUFFICIENT PV-H_2 ALTERNATIVE ENERGY OBJECTS

Описується розробка універсальної технології, яка може бути використана для забезпечення безперервної потужності для малих і середніх автономних об'єктів або їх мікро-сіток з використанням альтернативних джерел енергії та системи акумулювання енергії. Показано, що технологія використовує передові розробки електролізерів водню і паливні елементи для ефективного зберігання надлишкової енергії, отриманої з поновлюваних джерел, для подальшого використання в паливних елементах.

Introduction

In order to reduce greenhouse gas emissions within the European Community and reduce its dependence on energy imports, the development of energy from renewable sources should be actively supported. The Renewable Energy Directive [1] establishes an overall policy for the production and promotion of energy from renewable sources and requires the EU to fulfil at least 20% of its total energy needs with renewables by 2020 – to be achieved through the attainment of individual national targets. Improvement the efficiency of wind energy infrastructure and solar energy sector using hydrogen as energy carrier storage technologies will significantly reduce the consumption of hydrocarbon fuels and will improve the environment in the most environmentally stressed urban areas and industrial regions.

The Ukraine is going through an economic crisis caused by Russian aggression in 2014. The resulting massive attack on Ukraine’s energy sector is one of the most important elements of Russia’s hybrid war against its neighbour. More than half of the Ukraine's primary energy supply comes from local uranium and coal resources, although natural gas also plays an important role in its energy mix. Ukraine consumed about 1.5 trillion cubic feet of natural gas in 2014, with domestic production accounting for 47% of the total at about 700 billion cubic feet. The remainder of supply is made up by Russian natural gas, imported through the Bratstvo and Soyuz pipelines [2]. Switching to renewables and increased energy efficiency are priorities especially important for Ukraine because it is one of the biggest energy consumers in the world [3]. The usage of fossil energy resources must be decreased – there are real concerns over the exhaustion of them and global climate changes due consuming them. Other concern is that local energy markets indicates increased dependency on energy imports. These factors make the development of alternative energy sources and usage of renewable resources an urgent matter for Ukraine researchers and policy makers to strengthen independence [4].

Ukrainian and especially Latvian energy balance of solar energy share is growing slowly and one reason is necessity for energy accumulation. Energy storage capacity is an important value must be planed for each solar/wind grid separately, depending on availability of local energy systems and actual geographic location. This article summarise experience of Ukrainian and Latvian researchers in scaling hydrogen energy technologies to facilitate energy storage in power systems operating from renewable resources.

Energy storage methods

A proper energy (electricity) storage can enhance the value of wind energy acquisition by dispatching that energy when it is needed rather than when it was originally generated. Multiple solutions are available and both fundamental as well as applied research in this field is still ongoing. The landscape of energy storage is extensive. The review of Sabihuddin et all, 2015 [5] has discussed 27 types of storage technologies. Some storage technologies are strongly coupled to particular generation technologies. Storage technologies have been compared numerically and qualitatively on the basis of such parameters as specific energy, energy density, lifespan, cycle life, self-discharge rate, capital costs of energy and power etc. (see Luo et all, 2015 [6]). For instance, pumped hydro storage (PHS) systems show strong similarities with hydro-electric plants and are often used in conjunction with nuclear facilities. Compressed air electricity storage systems (CAES) are much like peaking gas turbine plants. Thermal storage systems are integral parts of thermal (and solar thermal) plants and are often used in the context of steam generation and waste heat recovery for subsequent power plant cycles. Flywheel systems (FWS), in comparison to CAES, are fairly mature and commercially tested [5,6]. They exhibit many advantages over both PHS and CAES solutions.

Most chemical energy storage systems have a number of common features, for instance: the electrodes, the electrolyte and the separators or membranes. Improvements have largely focused on materials [5]. A shift has occurred towards more reactive electrodes. These more reactive variants have shown the promise of increasing energy and power densities—the use of lithium (e.g., Li-Ion batteries) and oxygen/air based chemistries (i.e., metal-air batteries) reflects this trend. Nevertheless virtually every chemical battery type has seen the utilization in different electricity storage systems.

Energy can be stored also using hydrogen as energy carrier, transforming electricity from renewables to hydrogen through electrolysis of water and storing this hydrogen in high pressure vessels, liquid form or as hydrides of specific materials [7]. Fuel cell (FC) is indispensable part in hydrogen storage system, as it increase in scale, operate much like traditional thermal generation plants, albeit converting fuel (hydrogen) directly to electricity. Fuel cells offer an alternative to burning, have high energy and power performance and have seen some commercial applications to large scale grid level storage/generation (Fig. 1).

However, there is a need, to reduce costs of hydrogen energy storage systems even further in order to be competitive with other energy storage solutions. Traditional chemical batteries are likely to be strong contenders for small/middle scale storage at this point, though with additional research metal-air chemistries may hold future promise [6, 7]. FC and FWS are tested in large and small scale applications; therefore, these systems may be more relevant to deployment for distributed grid infrastructure [6]. For long-term storage (months, years) the hydrogen energy storage is competing not so much with overall efficiency (below 60%) but costs, ease of installation and multipurpose usage (electricity, heat and fuel for transport), see [5–7].

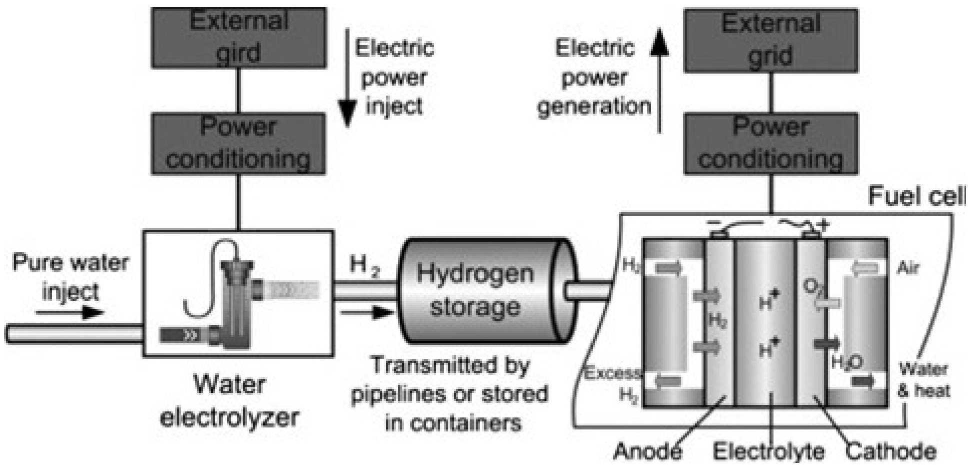

Fig. 1. Topology of hydrogen storage system (electrolyser, storage vessel and fuel cell (after Luo et all, 2015)

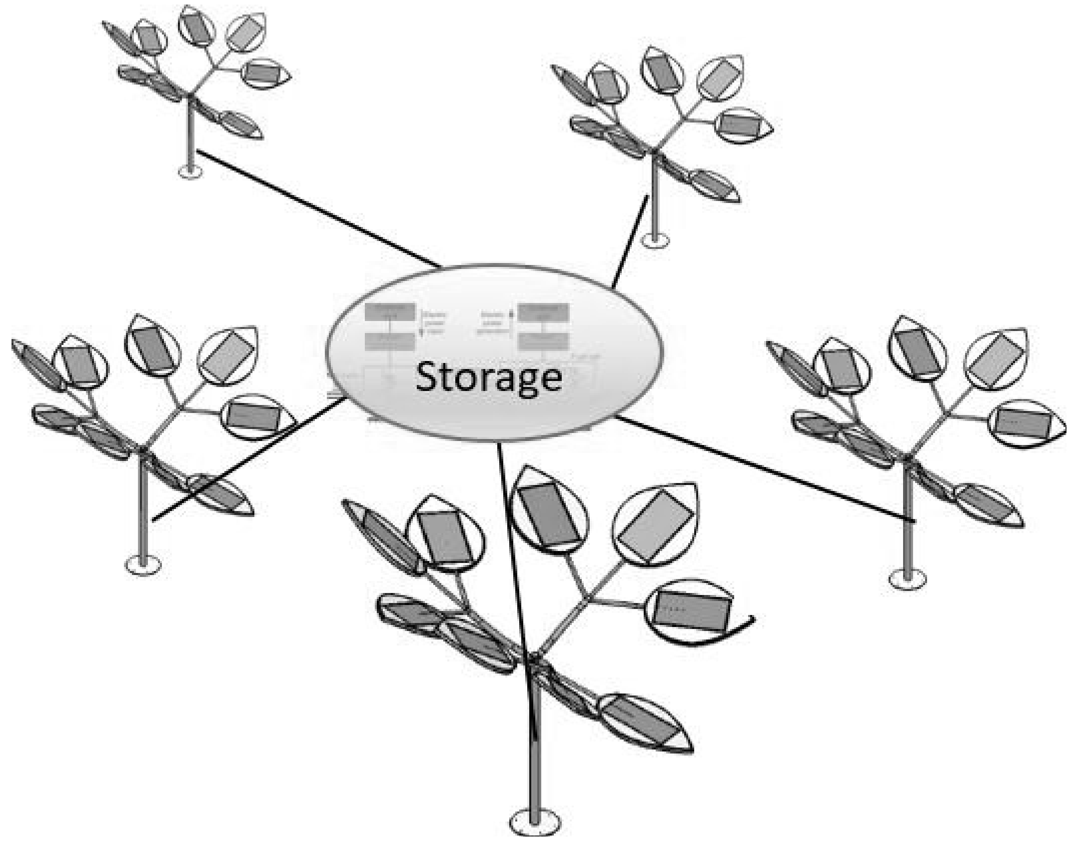

Fig. 2. Principal scheme of micro-grid from 5 solar trees (light poles)

Despite the search for new ways to produce environmental friendly fuels, the focus of research is still concentrated on the possibility of producing hydrogen from water [7, 8]. Technology of hydrogen production based on the processes of decomposition of water by electrolysis, are widely used in various fields of modern industry. Compared with other methods of producing hydrogen, electrolysis is easy flowsheet feedstock availability and relative ease of maintenance of power plants. Therefore urgent problem is the development of electrochemical technologies to generate hydrogen from water with minimal cost of electricity, especially in light of the expansion of the use this hydrogen as resource for environment-friendly energy in advanced technologies.

Experimental details. A real experiment is expected this summer, the description of the experiment in the study as planned is outlined. Micro-grid of 5 solar lighting poles (PV 200W and LED 100W each – see Fig. 2) as prototype of renewable energy plantation and consumer simultaneously, self-made 2 different electrolysers (high pressure and pulse powered) connected with hydrogen storage in compressed gas cylinder and metal hydride tank accordingly will be referred as potential long-period energy storage facilities.

Transformation of excess energy to hydrogen wia water electrolysis. In industry, widely used conventional electrolytic liquid alkaline electrolyte to ensure the generation of gases at a pressure of 0.05 - 1.6 MPa in the temperature range from 333 K to 353 K and a current density of 1200-2500 A/m^2 [8]. Thus the energy consumption (depending on the process temperature, pressure, quality of the electrode cell design, and other factors) vary in the range from 4.3 kWh/m^3 to 5.2 kWh/m^3 of hydrogen (H_2).

High pressure electrolysis

At the A. N Podgorny Institute for Mechanical Engineering Problems has developed a technology of electrochemical production of hydrogen and oxygen a high pressure using a getter electrode diaphragm-less cell design [9, 10]. Designed electrochemical method for the decomposition of water is a cyclic, consisting of alternating time processes hydrogen and oxygen. Operating temperatures developed electrolytic process is in the range of 280 K to 423 K, and a pressure range of 0.1–70 MPa. The electrolyte is proposed to use a 25% aqueous solution of alkali. In the proposed technology, the cyclic nature of distribution to the consumer gases H_2 and O_2, the reaction of water decomposition takes place continuously with simultaneous evolution of hydrogen and oxygen in an electrochemical cell. In the first half-cycle, hydrogen is released at the passive electrode in a gaseous form and fed to the high pressure line, and oxygen chemically bonded to the active electrode (forming a chemical compound). In the subsequent half-cycle is carried out electrochemical hydrogen reduction of the active electrode is accompanied by the release of oxygen on the passive electrode and the selection of an external pipe

Pulse electrolysis

Typically direct current (DC) power is used in electrolysis; nevertheless pulse DC voltage also can be used [11-13]. Bockris et all [11] found that applying voltage pulses on an electrolysis cell, the long current tail is observed just after end of voltage pulse. Shimizu et all [12] used inductive voltage pulses (200 ns) to power electrolysis cell and found that efficiency of electrolysis does not change with changing applied power. Researchers from Institute of Solid State Physics, University of Latvia [12] used inductive voltage pulses to compare different metals as cathode and found that concentration of dissolved hydrogen grows faster on metals with higher hydrogen evolution overvoltage and lower hydrogen solubility. In this work we prove the fact that using inductive voltage pulses to power electrolysis cell, it is possible effectively reduce applied potential thanks to the possibility to separate both the charging current from the charge transition (Faradic) current in hydrogen evolution reaction.

Energy Storage. Battery, hydrogen and hybrid energy storage will be analysed for particular case – 5 small solar lighting poles (200 W each) are connected in micro-grid with total installed power 1 kW. LED lights for each pole has maximum 100 W, electric system is designed to 12 V and nominal current – 1 A. With smart power regulation (motion sensors in every pole) it is possible to reduce consumed power five times, accounting to micro-grid of 5 poles – from 0.1 to 0.5 kW. Volumes of energy necessary to be stored are calculated from actual amount of electricity to be consumed. In our case two consumption scenarios – one for particular day and second for average year must be combined. Daily amounts of harvested energy from the sun and the consumed in dark time is highly variable through year and for latitudes of Riga (Latvia): 56°57'0"N/24°6'0"E and Kharkiv (Ukraine): 49°55'0"N/36°19'0"E varies between 0.5–12.23 kWh/m^2 (Riga) and 1.67–12.12 kWh/m^2 (Kharkiv) [14].

The number of hours the sun is shining each day that is the number of hours between sunrise and sunset each day when averaged over the year, are 12 hours per day multiplied by number of days in year everywhere in the world. Only in the Northern latitudes the average intensity is lower than at the Southern latitudes. Harvested energy from 5 poles is surplus in half a year (summer time) and deficit in winter time (Figure 3, calculated from [15]).

The hydrogen is produced in water electrolysis using two different electrolysers. When high pressure electrolysis is used, typical gas vessels up to 200 bar can be connected directly to store hydrogen for winter time. Low pressure electrolysis (below 3 bar) is second option to produce hydrogen from water, and such

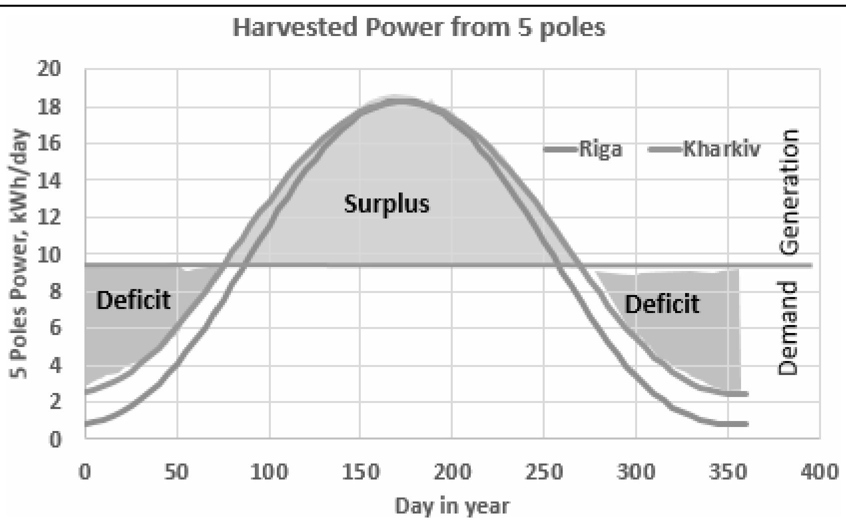

Fig. 3. Annual solar generation versus demand for a solar system at latitudes of Riga (57N) and Kharkiv (50N)

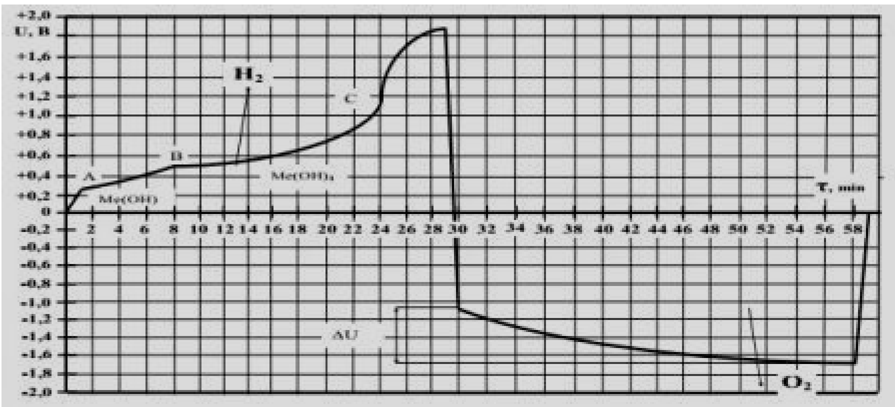

Fig. 4. Change of voltage for hydrogen and oxygen isolation in the electrolysis process:
Current density I = 200А/м2; (A–B) – working area of the hemicycle; (B–C) – area of operation when there are the additional power inputs; ΔU – overvoltage under reduction of the active mass.

hydrogen can be easily stored in metal hydride tank for utilization in winter time. Low temperature can decrease pressure of stored hydrogen in both cases (pressed and bind in crystal lattice), therefore it is desirable to place storage below ground at least 1 m depth, where constant temperature is the year-round.

Electricity generation. Proton electrolyte membrane fuel cell stack (PEMFC) 1.5 kW is used to generate electricity from stored hydrogen. As it could be understood from Fig.4, the need for additional electricity will arise of the dark and cold season only.

Results and discussion

High pressure electrolysis. The proposed technology of electrolysis for producing hydrogen and oxygen at high pressure eliminates the cost of electric energy transfer resistance separation membranes due to their absence [9,10]. This ensures the generation of H_2 (O_2) under high pressure, up to 200 bars with no necessity for additional compressor. The advantage of the described method for obtaining hydrogen include the ability to relatively simple (adjusting current) to control the reaction rate and, therefore, energy consumption, which is especially important when used as the primary source of renewable energy (solar, wind), differing volatility are received.

The process of hydrogen generation begins with applying negative potential to the passive electrode (Fig. 2). The gas-absorbing active electrode operates as an anode at this stage. The water-dissociation reaction produces hydrogen and oxygen simultaneously. The hydrogen is isolated at the passive electrode in the gaseous state, and the oxygen is chemically combined at the active electrode (i.e., it is accumulated as an oxide). This operational sequence is provided by automatic switching of electrodes to act as anode/cathode electrodes.

Supplying the electrolysis cell with electric power is synchronized with an electromagnetic switch that controls the gas flow. As a result, hydrogen is isolated under high pressure and only fills a hydrogen pipeline. In the same manner, oxygen is fed to a separate pipeline. The water-dissociation reaction is initiated by increasing the voltage at the electrodes during the gas-generation process. Automatic control of the gas-generation process is based on the process's voltage-current characteristics, which were determined experimentally.

Pulse electrolysis is developed for efficient low-pressure electrolysis**.** The voltage to split water in practical electrolysis devices is higher than thermo-neutral cell voltage due transformation into heat, which heats up the cell. Therefore industrial electrolyser requires additional cooling and the value of DC voltage is defined [15]:

$$E = E_{rev} + loss,$$

where the loss is:

$$loss = E_{anode} + E_{cathode} + E_{mt} + IR,$$

where E_{anode} – activation overvoltage of the anode; $E_{cathode}$ – activation overvoltage of the cathode; E_{mt} – overvoltage of the mass transfer; IR – ohmic overvoltage (includes resistance in an electrolyte, on electrodes,

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leads). Current density must be higher than 100 mA/cm^2 in industrial electrolysers, therefore voltage applied to individual cell partly transforms into the heat, becoming typical loss in DC water electrolysis [16].

The transition from the rapid charging to slow discharge tail happens through the breakpoint. By changing spacing between electrodes, the charging amplitude voltage pulse changes – at 5 mm distance the rapid charging end at about 5 V, while reducing the distance between the electrodes to 3mm and 1mm, the voltage value at the end of the charge drops to 4,2 V and 3,8 V respectively. To find the effective value of voltage taking into account the possible charge separation between cell's geometric capacitance and the electric double-layer charging with following Faraday reactions, the voltage oscillograms are modified to be compared with DC electrolysis. Comparison of volt-ampere curves shows that in the weak and also in 0.1 M KOH solution pulse electrolysis is intense as the DC mode - slope is almost twice steeper. By contrast, in 0.3 and 0,5 M KOH solutions the steepness of pulse electrolysis volt-ampere curve is almost the same as the DC mode. This confirms discussed above hypothesis that the inductive voltage pulse in rapid growing phase is charging only geometric capacity of electrolysis cell, and only then the charging of the electric double-layer capacity and parallel starting charge transfer (electrolysis) process. High power short pulse generator is elaborated to power 1 kW electrolysis unit with efficiency close to 67%.

Energy production, consumption and storage. From installed power of solar PV – 1 kW in micro-grid, it can be calculated maximal annual harvested energy – 1k W $\times$ 164 days $\times$ 24 h = 3936 kW·h, in case all days are sunny and all modules are perpendicular to Sun. In Latvia the sun shines average 1,790 hours per year, which is around half of the possible sunshine duration (clear weather). In Latvia most sunny days - an average of 28 to 30 – are from May to August, when the sun shines an average of 8–10 hours per day. By contrast, in November, December and January 10–12 days with the sun shines an average of only 2–3 hours a day [17]. In our case it means, that around 1790 kWh can be harvested from PV panels in an average year. The consumption is calculated to be in average half of production, therefore to ensure that the accumulation has a reserve, assumption is done that our storage facility must be with energy capacity around 800 kW·h. If we want to store this energy amount in batteries, the pack with capacity 66.7 kAh is necessary (800 kW·h equals battery packs from 10 Tesla EV). Tesla (Company producing most powerful electric vehicles) has just announced (2015, Forbes.com) that it will sell a battery pack for home use that will cost approximately $3500 for 10 kWh of power, than for 800 kWh it would be $280000. Hydrogen has one of the highest energy density values per mass. Its energy density is between 120 and 142 MJ/kg or 33–39 kWh/kg [18]. This means that for storage of 800 kWh it is necessary about 25 kg of hydrogen or 26 reservoirs each 50 l and pressure 200 bar or 260 Nm^3 (gas at normal conditions). To produce such amount of hydrogen in summer time in average 700 hours it is necessary electrolyser with capacity around 350 l/h.

Conclusions

In this paper innovative methods of water electrolysis are described – high pressure hydrogen gas generation up to 200 bar, and short pulse electrolysis of hydrogen gas at low pressure up to 3 bar. Both hydrogen-generation systems allow the chemical reaction rate to be controlled by controlling the current intensity (high pressure electrolysis) or pulse sequence rate (pulse electrolysis). This is especially important when the primary energy source for the electrolysis device is Sun or Wind with unpredictable and variable power affected by seasons, night/day changes, and climatic factors. Both investigated electrolysis technologies have shown high promise for use in the small and medium-sized self-sufficient objects or their micro-grids in combination with high-pressure or metal hydride hydrogen storage facilities.

It is calculated in case of 1 kW solar PV/0.5 kW LED lights micro-grid, the storage facility with capacity of 800 kWh is necessary. This amount of electricity can be recovered from 32 kg or 350 Nm3 hydrogen gas, and to produce such amount of gas with electrolysis system having capacity 350 l/h, the 112 sunny days in summer time are necessary.

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