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AUTOMATED SYSTEM OF SELECTION MULTIPLE UNITS ROLLING STOCK ROLLING STOCK FOR CONVERSION TO HYDROGEN FUEL

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АВТОМАТИЗОВАНА СИСТЕМА ВИБОРУ МОТОРВАГОННОГО РУХОМОГО СКЛАДУ ДЛЯ ПЕРЕВЕДЕННЯ ЙОГО НА ВОДНЕВЕ ПАЛИВО

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АВТОМАТИЗИРОВАННАЯ СИСТЕМА ВЫБОРА МОТОР-ВАГОННОГО ПОДВИЖНОГО СОСТАВА ДЛЯ ПЕРЕВОДА НА ВОДОРОДНОЕ ТОПЛИВО

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The article considers options for using hydrogen as a fuel for multiple units rolling stock in Ukraine. An analysis was made of the rolling stock with its use in Japan and Germany. Considered fuel-economic indicators of operation of motor-wagon rolling stock in Ukraine at the moment and with the use of a proton-exchange membrane fuel cells on this rolling stock, the comparison and analysis of the data. Was created model for estimating the rolling stock on hydrogen fuel and determining the most efficient vehicles for modernization using proton exchange membrane fuel cells. Pre-determined the necessary equipment for modernization, creating a scheme for locating equipment on the rolling stock.

Key words: *hydrogen fuel, modernization, diesel rolling stock, fuel cells, polymer exchange membrane, fuel consumption.*

У статті розглянуто варіант використання водню в якості палива для мотор-вагонного рухомого складу в Україні. Проведено аналіз рухомого складу з його застосуванням у Японії і Німеччині. Розглянуто паливно-економічні показники експлуатації мотор-вагонного рухомого складу в Україні на даний момент з використанням протон-обмінних мембранних паливних елементів на цьому рухомому складі, проведено порівняння і аналіз отриманих даних. Розроблено модель оцінки рухомого складу на водневому паливі та визначено найбільш ефективний рухомий склад для модернізації з використанням протон-обмінних мембранних паливних елементів. Попередньо визначено необхідне обладнання для модернізації, розроблена схема розміщення обладнання на рухомому складі.

Ключові слова: *водневе паливо, модернізація, дизель-поїзд, паливні елементи, полімер обмінна мембрана, витрата палива.*

В статье рассмотрен вариант использования водорода в качестве топлива для мотор-вагонного подвижного состава в Украине. Проведён анализ подвижного состава с его применением в Японии и Германии. Рассмотрены топливно-экономические показатели эксплуатации мотор-вагонного подвижного состава в Украине на данный момент с использованием протон-обменных мембранных топливных элементов на этом подвижном *составе, проведено сравнение и анализ полученных данных. Разработана модель оценки подвижного состава на водородном топливе и определен наиболее эффективный подвижной состав для модернизации с использованием протон-обменных мембранных топливных элементов. Предварительно определено необходимое оборудование для модернизации, разработана схема размещения оборудования на подвижном составе.*

Ключевые слова: *водородное топливо, модернизация, дизель-поезд, топливные элементы, полимер обменная мембрана, расход топлива.*

Formulation of the problem. Railway transport provide about 50 % of all transportation in Ukraine [1]. Most of the rolling stock in Ukraine is now lagging behind the worldwide technical progress for several decades (operated rolling stock and technologies of its repairing, to a greater extent, belong to second generation, and they are morally obsolete In Ukraine most of science researches, in general, focused on developing technologies, most of each aimed on solution of the problems, related to the extension of service life of now operated rolling stock. Also, is being conducted developing and production new, modern rolling stock on Ukrainian factories, including rolling stock for high-speed operation. As an example, Ukrainian manufacturer "Kryukov Rail Car Building Plant" designed and produced electric train EKr-1, named "Tarpan", with a maximum allowable speed of operating 220 km/h [2]. But at the moment, maximum allowable speed of operating on Ukrainian railroads is 160 km/h, the reason is that existing railway track does not allow operate rolling stock with higher speeds.

In view of the world trend of increasing the speed of passenger rail transport and make it zero emission, for Ukraine becomes relevant the question of its own high-speed and zero emission operations. To operate railway rolling stock with speeds higher 200 km/h, railway track should be built from zero (which is corresponding to the norms of operation), this entails a number of financial costs. According to Private Joint Stock Company "Ukrzaliznytsya" strategy presentation till 2021, dated September 12, 2017, Ukraine is planning spend 5.9 billion USD of capital investment for railway development, from which 4 billion is for the renewal of rolling stock [3].

One of solution could be using, on traction rolling stock with the hybrid power transmission, proton exchange membrane fuel cells (PEMFC). As well, known as polymer electrolyte membrane fuel cells (PEM). That will reduce fuel costs, the level of environmental pollution and noise pollution. From our point of view, it is the most perspective topic for railway rolling stock development for next 15-20 years. This topic will be relevant until the moment when will be created power storage which could provide enough power for rolling stock operation, without frequent re-charging, and at the cost-effective price. Therefore, consideration of using hydrogen as a fuel on multiple units rolling stock currently is relevant and timely objective.

Purpose and objectives of research. The main objective of this research is the technical and economic improvement of the operational index of the railcar rolling stock by modernizing it replacing the power plant (diesel ICE) with polymer electrolyte membrane fuel cells. To solve the set goals, the following tasks are considered:

- Review experience of using hydrogen as fuel on traction rolling stock in other countries;
- Determination of the most efficient use of hydrogen as a fuel;
- Analysis of scientific research and testing of rolling stock with PEMFC;
- Consideration methods of obtaining, transporting, storing of hydrogen and the operation of PEMFC;
- Comparing the indicators of fuel efficiency on the rolling stock in operation

with its modernization and the definition of its rating;

• Development of the basic scheme of rolling stock operation during its modernization with PEMFC.

The object of the research is: determination of multiple units rolling stock fuel efficiency index, when it is modernized with replacement power plant (diesel ICE) with PEMFC.

Overall information about using hydrogen fuel on railway transport. Today exists two variants for using hydrogen as a fuel on railway transport.

- Using hydrogen as a fuel for internal combustion engines. In this case expediently applying hybrid power transfer circuit, when the power point producing electricity, which flows to batteries and then, with the help of smart allocation system of energy, flows to various units of rolling stock [4];

- Installation on rolling stock fuel cell, whose operating principle based on electrolysis (more precisely on its reverse process). This variant more effectively could work with hybrid power transfer circuit (with batteries and smart allocation system of energy) [5, 6].

One of the first tractive rolling stock, which powers with hydrogen fuel, built scientists from Tokyo Railway Research Institute (Japan) in 2001. K. Ogawa, T. Yamamoto, T. Yoneyama in the period from 2001 to 2005 year tested, by that moment first in the world, rolling stock with PEMFC. Rolling stock weight, including auxiliary equipment, was 35.3 tons. According to [5] research was conducted by two schemas of power transfer circuit (fig. 1).

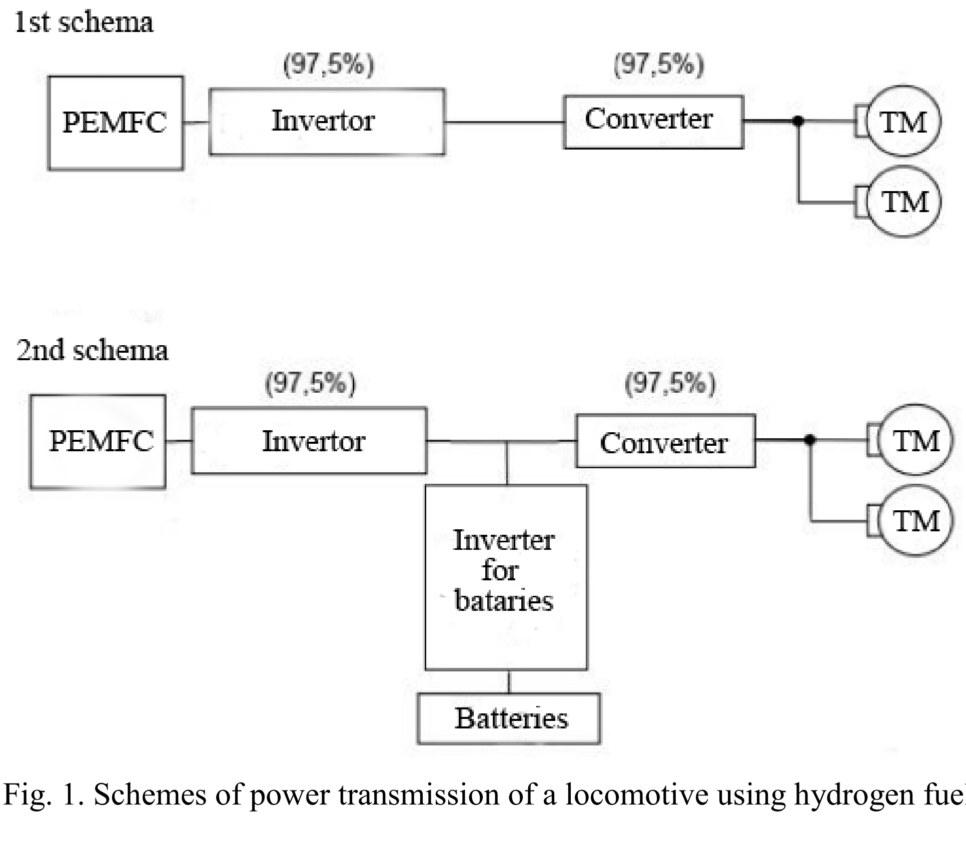

Fig. 1. Schemes of power transmission of a locomotive using hydrogen fuel

First schema: PEMFC (with max output power 120 kW) - Converter - Inverter - Traction motors. According to the results of tests mid index of efficiency was equal 56.3 %, and fuel consumption was 11.3 km/kg.

Second schema: PEMFC (with max output power 120 kW) - Converter - Li-Ion batteries - Inverter - Traction motors.

If in first schema electricity flow almost directly from PEMFC to traction motors, then with this power transfer scheme PEMFC charging Li-Ion batteries, then it flows to traction motors. Likewise, during tests of this schema were used regenerative braking, down to 5 km/h, then electro-pneumatic brakes.

According to the results of tests mid index of efficiency was equal 75.7 %, and fuel consumption was 16.1 km/kg [5].

In 2016 French company Alstom represent, on “Innotrans 2016”, prototype of commuter train which runs on hydrogen fuel. Coradia iLint designed and built on Lint 54 base, by Alstom in common with German center of Aerospace Industry (project name "Bethy"). Hydrogen is converting into electrical energy in PEMFC and runs traction motors. Hydrogen stored in 2 tanks by 90 kg each on the roof of rolling stock. On every rolling stock established 2 PEMFC, with power 200 kW each. PEMFC are supplied by Canadian manufacturer "Hydrogenics", between "Alstom" and "Hydrogenics" was signed a contract according to it "Alstom" will receive at least 200 PEMFC in next 10 years, sum in the contract (excluding repairing and service) amounted to 50 million euro. Drive unit provide starting pulling force 87 kN and power 544 kW. Other spare parts are used similarly to the current diesel version. As batteries installed 110 kWh Li-Ion accumulators, placed under the salon of rolling stock. The energy recovery system is also used on this rolling stock. At full refueling of fuel tanks travel distance of Coradia iLint is between 600 and 800 km, from which follows, that fuel consumption variable 6.667 - 8.889 km/kg, with a maximum speed of movement 140 km/h. Alstom planning use hydrogen to refuel trains from Industriepark Höchst (one of the biggest chemical and pharmacy factory in Europe), where hydrogen is a by-product [6, 7].

Overall information about hydrogen. Hydrogen is the most common chemical element in the universe. The hydrogen gas has no taste, no color, no smell and it’s not toxic. At certain concentrations and interaction with the oxygen in the environment - explosive. Has a specific heat of combustion of 120 (lower threshold) - 140 (higher threshold) MJ/kg (for comparison, the specific heat of combustion of natural gas=50 MJ/kg, propane-butane =36 MJ/kg, gasoline (92) = 42-44 MJ/kg, diesel = 42.7 MJ/kg) [8].

Hydrogen is produced both on an industrial scale and on a laboratory scale. In the industry to date, the following methods of obtaining hydrogen have been widely used:

1. Conversion (process of processing of gases for the purpose of changing the composition of the initial gas mixture) of natural gas or methane with steam at a temperature of 800 to 1300 °C. In this way, more than half of all hydrogen used in the world is produced. Although this method is currently the most popular, it still remains not environmentally friendly. According to the formula below, we can see that along with hydrogen in the ratio ⅓, a CO is formed, which must be disposed of, which ultimately affects not only the ecology of the environment, but also the cost of produced hydrogen.

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 .$$

2. Transmission of water vapor over the heated coke at a temperature of about 1000 ° C, without access to oxygen.

$$H_2O + C \leftrightarrow CO \uparrow + H_2 \uparrow .$$

3. Electrolysis of aqueous solutions of salts, transmission of electric current:

$$2NaCl + 2H_2O \rightarrow 2NaOH + Cl_2 \uparrow + H_2 \uparrow .$$

4. Catalytic oxidation of hydrocarbons with oxygen:

$$2CH_4 + O_2 \leftrightarrow 2CO + 4H_2 .$$

5. Cracking and reforming are also used.

6. In 2007, a group of scientists from the UK published their research on the production of hydrogen in the decomposition of organic waste. According to their calculations, when decomposing organic waste, it is possible to collect hydrogen of grade A. By an approximate calculation from the organic waste of only London, 67 to 141 tons of hydrogen can be daily produced.

7. Production of hydrogen as a by-product from the pharmaceutical industry [9].

The cost of produced hydrogen depends on the method of its production and is in the range from $ 1 to $ 7 per kilogram. It is also very important to note that liquefied hydrogen must be stored under special conditions. Scientists from the USA developed special cryogenic tanks (cylinders, tanker) for safe and economically profitable storage and transportation of liquefied gases [10].

The next questions that arise are the volume of liquefied gas, its weight and cost in Ukraine. The weight of one liter of liquefied hydrogen is 70.99 g (0.07099 kg). At the retail price of a 40-liter gas cylinder at 500 hryvnias (~ $ 18.88) as of the NBU exchange rate for 16-11-2017), the cost of 1 liter of hydrogen is 12.5 hryvnia (~ $ 0.472), and the cost of 1 kilogram of hydrogen is therefore 176.08 hryvnia (~ $ 6.85). In a more detailed study of this market, it is likely that with wholesale purchases, the price of hydrogen will be much lower [11-13].

To store liquid hydrogen, it is necessary to use storage with efficient thermal insulation. For long-term storage and also when transporting liquid hydrogen, in order to minimize losses from evaporation, it is recommended that it be maintained in a supercooled state. The use of multi-layer insulation on cryogenic equipment, in the USA, has shown that it is one of the most important conditions for the safe long-term storage and transportation of liquid hydrogen in large quantities. Tests were carried out on a transport tank with a capacity of about 107,000 liters, with an insulation thickness of 28.757 millimeters, evaporation losses were only 0.25 % per day, including losses from heat influx on the supports. Currently, such tanks, with a capacity of 96,200 liters, are widely used for transporting liquid hydrogen in the United States, with total losses less than 10 % of the mass of the liquid product per year [14-17].

Consider the principle of operation and the use of proton-exchange membrane fuel cells, they are a type of fuel cells that are used mainly for transport applications, as well as for stationary and portable applications. Their distinguishing features are lower temperature ranges (from 50°C to 100°C), pressures and a special proton conductive polymer electrolyte membrane. PEMTE generate electricity and operate on the principle of the opposite electrolysis. They are the main candidate for replacing the aging alkaline fuel cell technology, which is widely used to date all around the world.

PEMFC consists of membrane electrode assemblies (MEAs). They represent a collected stack of proton exchange membranes or ion-exchange membranes, catalyst and a flat electrode plate used in fuel cells and electroliers. The main part of the cell is the triple phase boundary, where the electrolyte, catalyst and reagents are mixed and, therefore, where the reaction takes place. It is important to note that the membrane should not be electrically conductive, it is necessary to prevent mixing of reactions. Operating temperatures, preferably, should be above 100 °C, so that the by-product - water becomes steam, and water management becomes less critical in the design of the cell.

Let's have a look at reactions inside fuel cells. The hydrogen stream is fed to the anode side of the PEMFC. On the anode side, it is catalytically split into protons and electrons. Hydrogen oxidation reaction at the anode represented below:

$$H_2 \rightarrow 2H^+ + 2e^- ,$$

$$E' = 0 \text{ V } dE'dT=0mVK^{-1} .$$

Formed protons penetrate the membrane of the polymer electrolyte on the side of the cathode. Electrons, in turn, move along the external load circuit also to the cathode side, thus creating an electric current at the outlet of the fuel cell. Meanwhile, the flow of oxygen flows directly to the cathode side. On the cathode side, oxygen molecules react with protons that have passed through the membrane of the polymer electrolyte from the side of the anode, and electrons coming through the outer chain, forming water molecules. The oxygen reduction reaction at the cathode is shown below:

$$12O_2+2H+2e \rightarrow H_2O$$

$$E' = 1.2291\ V\ dE'dT= -0.8456\ mVK^{-1}.$$

Proceeding from this, the general reaction is as follows:

$$H_2+12O_2 \rightarrow H_2O$$

$$E' = 1.2291\ V\ dE'dT= -0.8456\ mVK^{-1}.$$

The reversible reaction is expressed in equations and shows the reincorporation of hydrogen protons and electrons together with the oxygen molecule and the formation of one water molecule. Potentials in each case are given with respect to the standard hydrogen electrode (fig. 2).

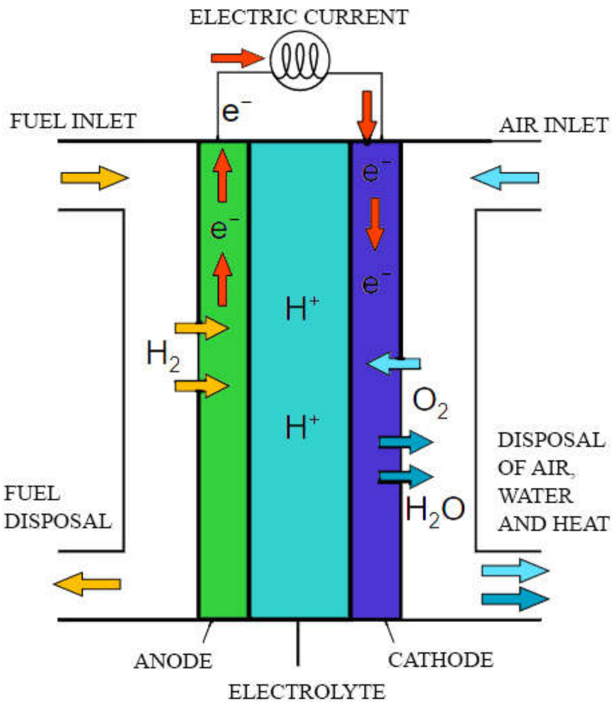

Fig. 2. Schematic diagram of the operation of a polymer electrolyte membrane fuel cell

On the basis of PEMFC, so-called hydrogen generators of different power are produced, from 1 kW to 4.6 MW, they have found their application in various industries. One of the leaders in the production of such systems is the previously mentioned company "Hydrogenics" (Mississauga, Canada) [18].

Using PEMFC on traction rolling stock in Ukraine

Comparison of fuel-economy indexes on operated rolling stock in Ukraine. Currently to compare different types of rolling stock, basically use two approaches. First directed to compare rolling stock cost of life cycle, and mainly used for already designed new project or modernized rolling stock [19]. Second approach based on qualimetrics approaches and used on early stages of choosing type of rolling stock or type of its modernization Main idea of this approach is in calculation of the technical level factor or other criteria and comparing under consideration types of rolling stock chosen by criteria [20]. In our case was chosen second approach.

To evaluate the rolling stock before and after modernization, a criterion was proposed that shows the cost of fuel, which is necessary for transportation of one passenger per one kilometer, expressed in moneyed equivalent.

$$CT_{p/km} = \frac{BSFC \cdot FC \cdot EP \cdot C}{AS};$$

where BSFC – brake specific fuel consumption, $^{g}/_{HPh\ (kWh)}$;

FC – fuel cost, uah / kg;

EP – engine power, HP (kW);

C – вauxiliary coefficient for converting the received value into UAH / pass * km;

AS – number of seats in rolling stock.

This approach was implemented in a subprogram on choosing the type of multiple units rolling stock rolling stock for transferring it to hydrogen fuel, which is included in the overall program for assessing the quality of rolling stock [20].

To ensure the possibility of using this criterion speed was chosen constant and equal 60 km per hour. The following prices were accepted for calculations: 28,67 UAH/kg for diesel and 1,77 UAH/kWh for electricity. [21-22] Brake specific fuel consumption, electricity and other needed data for calculations were accepted according to technical specifications of multiple units rolling stock rolling stock [23-34]. Specific hydrogen consumption and needed power of PEMFC for modernizations accepted according to the analysis of the “Alstom” company reports [7, 35].

Calculations were made for multiple units rolling stock rolling stock, which is operated on the Ukrainian railways: DR1A, D1, DPL1, DPL2, DTL1, DTL2, 620M, 630M, DPKr2, ER2, EPL2, ED4, ET2, ER9M, EPL9T, ED9M. The results of calculations are presented in table 1.

The results of comparison showed, that the cost of fuel, when replacing the power plant by PEMFC on diesel powered trains decreases on about 60 %, but on trains which runs by electricity, increase on 159.9 %. Consequently, a cost-effective to use PEMFC on diesel trains. When choosing a prospective rolling stock to continue research work, taken into account indexes of rolling stock remaining service life. For further work chosen diesel train DPKr2, today in Ukraine only one such a train is operating. That means, that to place on it PEMFC it is necessary to build new rolling stock, with initially installed PEMFC on it (fig. 3).

To use hydrogen power plant on the rolling stock preliminarily needed next equipment:

- PEMFC HD series, power 200 kW, produced by “Hydrogenics”;
- Cryogenic fuel tanks, to storage hydrogen under the pressure 70 MPs, with volume 1300-1500 liters;
- Li-Ion batteries ~ 220 kW;
- Bogies (TMF 59-38-4) with traction motors.

Conclusions:

1. The experience of using hydrogen as a fuel on a rolling stock is considered. According to fuel-economy indexes chosen PEMFC as a power plant. As well using PEMFC increase number of moving parts inside power plant, what will decline wear and tear and will make repairing much easier during rolling stock operation.

Table 1

Indexes of efficiency of using hydrogen as a fuel on multiple units rolling stock rolling stock

Serial of rolling stock	DR1A	D1	DPL1	DPL2	DTL1	DTL2	620M	630M	DPKr2	ER2	EPL2	ED4	ET2	ER9M	EPL9T	ED9M
Diesel price, uah/kg	28,67									1,77						
The cost of diesel fuel for the transportation of 1 passenger per 1 km, uah	0,257	0,215	0,301	0,456	0,294	0,327	0,363	0,354	0,429	0,123	0,027	0,127	0,252	0,106	0,107	0,121
Brake specific fuel consumption of ICE, g/hp*h	170,0	168,0	160,0	158,5	160,0	158,5	140,0	140,0	163,45	4400	960	4700	4800	3640	3520	4400
Engine power, hp	2001	1074	2000	3060	2000	2250	516	1033	1591	1050	1040	1088	560	1010	968	1068
Number of seats, pieces	632	400	508	508	520	520	95	195	289							
Brake specific fuel consumption of PEMFC, g/hp*h	28,01									38,1						
Liquid hydrogen price, uah/kg	120,6									120,6						
Needed power of PEMFC, hp	1026	551	1026	1569	1026	1154	265	530	816							
The cost of hydrogen fuel for the transportation of 1 passenger per 1 km, uah	0,091	0,077	0,113	0,173	0,111	0,124	0,156	0,152	0,1589	0,320	0,070	0,330	0,656	0,276	0,278	0,315
Delta of expenses, uah / %	0,165	0,138	0,187	0,282	0,183	0,202	0,206	0,201	0,271	0,197	0,043	0,203	0,403	0,169	0,171	0,194
	64,46	64,03	62,24	61,88	62,24	61,88	56,84	56,84	63,03	-159,9	-159,9	-159,9	-159,9	-159,9	-159,9	-159,9

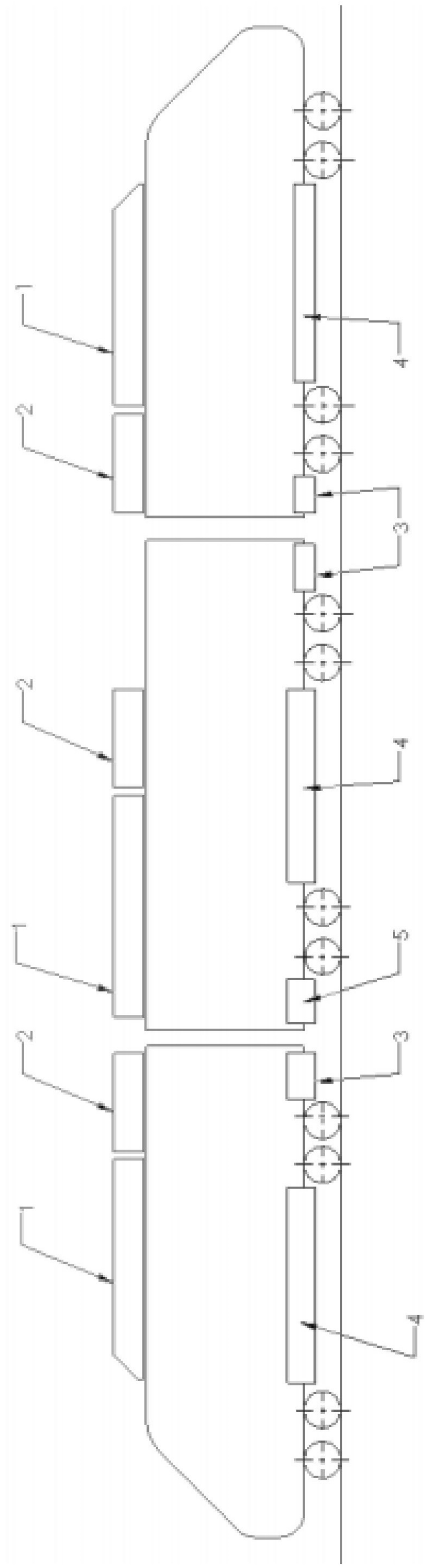

Fig. 3. Location equipment on a multiple units rolling stock with hydrogen fuel:
1 – Fuel tank; 2 – PEMFC; 3 – Invertor for traction motors; 4 – Li-Ion batteries; 5 – Invertor for indoor needs

2. The main methods of hydrogen production are determined; the average cost of liquefied hydrogen is taken equal to 120.6 UAH / kg. The fuel and economic indicators of the operated passenger rolling stock are compared. Comparison of cost indices for transportation of passengers using diesel, electric and hydrogen traction is made. It was preliminary concluded that it is economically feasible to use PEMTE as a power plant on diesel trains, taking into account the wear and tear during operation of rolling stock with PEMFC, the diesel train DPKr2 was chosen, after fuel cells are installed, the fuel costs will decrease by 63.03 %.

3. A scheme for locating equipment on rolling stock is proposed. The main technical parameters of the equipment for installation are determined.

4. In addition to saving fuel, the traction rolling stock will be absolutely environmentally friendly, because the by-product of the PEMFC operation is water (which can be used in itself needs), производство топлива возможно без выброса вредных веществ в атмосферу. Such a rolling stock in about 2 times quieter than similar diesel train.

5. In subsequent work, it is necessary to develop systems using PEMFC on a diesel train DPKr2, conduct rolling stock tests with PEMFC, simulate the operation of such rolling stock, calculate the payback period, design the logistics of production and supply of hydrogen to the points of refueling in the conditions of Ukraine.

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