Analysis of maximum braking power for determination of energy storage device characteristics within fuel cell electric bus

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Abstract. The article describes development of hydrogen energetics over the 2014 to 2018 period. There are statistic data about significant influence of hydrogen vehicles on that energy sector. The development of this means of transport is funded by the governments in different countries and that means big prospects for that technology. Modern researches especially are targeted at optimal approach searching to drive the electrochemical generator (fuel cell) as an initial energy source in the united energy plant. The offered approach is based on the movement characteristics data which were obtained from operated on the real city route trolleybus. The preference is given to use the experimental data for further synthesis of the city fuel cell bus model.

1. Introduction

Hydrogen fuel cells (HFC) sector continues its growth. Thus, in comparison with 2017 production costs have been reducing, FC market has involved new participants, and major producers of FC such as “Plug Power”, “Ceres Power”, “Hydrogenics”, “Ballard”, “Caetano” and “FuelCellEnergy” have invested millions of dollars in this industry development. In 2018 the total power put into service FC account for 145 MW, which corresponds with 74000 devices. Approximately 11000 FC vehicles were developed in 2018.

Table 1. Dynamics of fuel cell transport development

| Year | Shipments (1000 units) | Megawatts |
|------|------------------------|-----------|
| 2014 | 2.9                    | 37.2      |
| 2015 | 5.2                    | 113.6     |
| 2016 | 7.2                    | 307.2     |
| 2017 | 10.6                   | 435.7     |
| 2018 | 11.2                   | 562.6     |

Asian markets forced the FC development. There are a substantial demand for this technology and a qualified human resource. Figure 1 shows the number of soled FC (1000 units) during the 2014-2018 period.
In 2017 «Hyundai» has announced the supply of 1000 units of transport with FC for Switzerland, tentatively starting a similar program in South Korea for the period up to 2022 planning to expand its production up to 40000 units per year. However, the absence of infrastructure, coupled with the difficulties of FC vehicles licensing slow the growth of production capacities. Many large cities consider this alternative because of existing restrictions for the diesel buses and stringent requirements for air purity. An adaptation of existing charging infrastructure for hydrogen is more profitable than installation of new electric charging stations. Besides, the speed of hydrogen refueling, and autonomous motion distance of hydrogen buses will be higher than analogues with batteries [1].

2. Fuel cell electric buses
Fuel Cell Electric Buses (FCEBs) are considered as a promising technology for environmentally save future cities. European countries have already followed a stable policy of this transport type integration in existing cities motor parks. The result of this policy is the program “Joint Initiative for hydrogen Vehicles across Europe 2” (JIVE 2) which is financed by interstate fund “Fuel Cell and Hydrogen: Joint Undertaking” (FCH-JU). In accordance with this program it is planned to purchase 152 FCEBs and then sell it in European cities. According to the results of JIVE 1 program, which has been running a year earlier, for a period up to 2023 a delivery of almost 300 FCEBs and several petrol stations to 22 cities in Europe are expected. Among the producers of FCEBs in Europe such companies as “Van Hool” (Belgium), “ebe EUROPA” (Germany), “Autosan” (Poland), “Mercedes/Evobus” (Germany), “Wrightbus” (Northern Ireland), “APTS/Phileas”, “VDL” (Netherlands, Belgium) should be mentioned. Major engineering centres of the hydrogen technologies implementation such as “Arcola Energy” (United Kingdom) have been also developing.

The main type of FC which is used in the FCEBs’ composition is Proton Exchange Membrane Fuel Cell (PEMFC). Other types of FC are less suitable for power generating or portable application [2]. The main characteristics of FC for a transport application are shown in Table 2.

| Power range | 1-300kW |
|-------------|----------|
| FC technology | Proton Exchange Membrane Fuel Cell (PEMFC) Direct Methanol Fuel Cell (DMFC) |
| Application | Fuel Cell Electric Vehicles (FCEV) trucks and buses rail vehicles autonomous vehicles |
3. Topologies of power plants and principled approach to a fuel cell control while driving

Existing power plants with FCEV are typically performed by a parallel hybrid type and differ in the number of DC/DC converters and electrochemical storage devices (ES) (Figure 2).

Accumulator battery (ACB), supercapacitor battery (SCB) as well as their combination (ACB+SCB) could be used as an electrochemical storage device [3]. The model of power plant control system based on the Fuel Cell Systems (FCS) must consider the characteristics of two energy sources in frequent starts and brake modes.

In general, this model can be performed according to the type of continuous operation of the FCS and FCS inclusions in certain required power values (Figure 2).

Thus, the approach (a) is characterized by the following aspects:
- FC life span is prolonged because in terms of chemical technology repetitive on/off modes have a negative impact on the device materials [4].
- The increasing of the hydrogen fuel consumption is possible.
- In continuous operation mode of FC (power does not fall below the value $P_{\text{min}}$) a load distribution with electrochemical storage should be kept so that total energy flow provides a required dynamic characteristics of traction drive.
- The continuous operation of FC can result in a recharging of electrochemical storage device in a regenerative braking mode.

The full movement cycle of FCEV by type (b) can be divided into several stages:
- “no-load operation” (FC switching on, time period $t_0 - t_1$);
• “acceleration mode” (FC power increasing up to $P_{\text{max}}$, time period $t_1 - t_2$);
• “speed increasing period” (movement by means of other storage, time period $t_2 - t_3$);
• “regenerative breaking” (FC is switched off, other storage get energy, time period $t_3 - t_4$).

To identify the characteristics of the FCS and electrochemical storage device, loads occurring inside the traction drive in real urban movement must be defined. The necessary measurements were made by means of on-board registrar for trolley running along the route in Novosibirsk (Russia).[5] Received statistical data helps to assess the level of average power consumption (traction drive) and speed.

The analysis of the average values within average intervals from 60 seconds to 120 seconds was held. Figure 4 shows that the approximation function of an average power to the average speed does not depend on the selected interval.

![Figure 3](image3.png)

**Figure 3.** Function approximation of average power ($P$ - averaging interval).

It must be considered that average power 25kW is enough for movement of 18t electrical bus with average speed within 20 km/h [6].

Other important data were obtained by on-board registrar is the maximum amplitude of braking power during movement on the route (Figure 5). That is necessary because power and capacity of energy storage device will have considered these numbers in terms of braking energy conservation and its rational use.

![Figure 4](image4.png)

**Figure 4.** Changing amplitude of maximum braking power during movement on the route.

Further analysis of obtained data was done in terms of statistical approach (Figure 6 and Figure 7). It is necessary for justify the next conclusion based on experimental data. The method of probability density and integral distribution was used [7].
This result makes it obvious that the braking power will not exceed 150 kW with the 95% probability. These restrictions mean that the power of the future energy storage device has not to be able to exceed this amount of electrical power. That will help to reduce financial costs and decrease mass of the transport vehicle.

4. Conclusion
This article presents an analysis of the hydrogen energy industry current status, particularly in the electric transport complex. The main directions of development and improving the availability of hydrogen transport were identified.

Possible power plants topology for hydrogen vehicles were investigated; special aspects of fuel cell power plants operating modes were determined at different principle approaches.

It is offered to use real operational data of existing urban vehicle to justify dynamic characteristics of hydrogen transport. An average approximating power function depending on the average speed was formed and based on obtained from onboard registrar data.

The power determination of an electrochemical storage device is one of significant tasks in that research. For this reason maximum braking power analysis was done. It is statistically approved that maximum braking power of 18t trolleybus will not exceed 150kW. That means that the power of the future buffer storage device should not be more than this amount of electrical power to absorb regenerative energy.
Further study will be focused on determination of energy storage device type and parameters, and of fuel cell systems characteristics. The development of the control system based on data presented in this article is going to be made.

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