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The control of the working parameters of car hydrogen fuel cell stack in urban traffic conditions

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ABSTRACT
The paper describes the study of the control of the hydrogen fuel cell stack for a car, which has been prepared on the example of a light vehicle, built for racing competitions. The issue included of the control of the hydrogen cell stack in the conditions of varied energy demand, occurring during urban traffic and selection of system parameters, using numerical model.

KEYWORDS: Regulation, optimization, hydrogen cell stack, fuel cell stack, hydrogen car

1. Introduction

Although car electric drive has been known for a dozen of years, it is this decade that it is becoming more and more widely used. The idea of the electric car with a battery has one big disadvantage which prevents it from wider commercial usage i.e. not satisfactory range of travel due to insufficient battery parameters. Therefore, the development of hybrid drives using combustion engines can be observed. In different hybrid systems the combustion engine can perform different functions [2]. On the one hand, the engine is directly used for driving a car with simultaneous alternator drive generating electric energy for powering electric engines or batteries accumulating the energy. On the other hand, combustion engine is used as a sole energy source for generating electric energy for electric engine drive.

The issue of the flows of mechanical and electrical energy and their accumulation and buffering is the key issue in these types of drives and the subject of many different technical solutions and research [1,5]. Hybrids drives owing to their degree of complexity form a temporary solution in the development of electric drives and to be more precise energy sources for these drives [2]. In the systems with only electric drives as energy source, hydrogen fuel cell stacks are used apart from batteries and combustion aggregates. Smart Power team [7] from the Silesian University of Technology, based on their experience in constructing innovative, energy saving electric vehicles driven by batteries, has decided to install in their newly constructed vehicle a complex driving set with hydrogen fuel cell stack instead of lithium ion batteries.

Hydrogen fuel cell stack is a device which generates electric energy from hydrogen that is supplied from the tank with the flow being controlled by a controller and a set of valves depending on the current demand and oxygen being supplied from the air. In the course of chemical reaction water is obtained which is the only redundant outcome that do not cause emissions. It is worth mentioning that in the course of reverse reaction –hydrolysis it is possible to produce hydrogen and oxygen after delivering energy to water in a proper way. Commonly, the cell set is enriched with a set of supercapacitors which play a role of an energy buffer since the possibilities of controlling the cell are not as great as in the case of batteries. The degree of complexity of the supply set of hydrogen fuel cell stack is much greater than battery supply however, the hydrogen fuel cell stack supply has no disadvantages of battery set i.e. short time of filling up with hydrogen and far greater range, resulting from higher energetic density of hydrogen. Therefore, introduction of this type of supply as a source of supply for electric cars allows us to get rid of drawbacks of batteries.

2. Hydrogenius

The prototype for HydroGENIUS vehicle is Bytel. Both of the vehicles are research electric vehicles which have been elaborated and constructed at the Silesian University of Technology by the Smart Power team which consists of academics and students. The vehicles have been constructed in order to carry research on the possibilities of reducing energy consumption in transportation and optimization of technical solutions for energy efficient and light electric vehicles [6], [8]. The final verification of the results happens during Shell Eco-marathon race (SEM) [3]. Bytel, has been initially prepared by Smart Power team as a vehicle with lithium ion battery supply , however, during its development the supply has been changed and the batteries have been replaced by a set of hydrogen fuel cell stack. Additionally, the drive system has been altered to use energy recovery system with modern BLDC engines with innovative, patent application, system of gears and clutches. Bytel took part in global Shell Eco-marathon race in 2015 in prototype version, getting to the top final 10 of the best cars and taking 7th place in the category UrbanConcept Hydrogen. Nevertheless, in 2014 when it was in the version of conceptual vehicle it took 12th place in the category UrbanConcept Battery Electric. In the consecutive version a vehicle with hydrogen fuel cell stack is being prepared called HydroGENIUS.

The Shell Eco-marathon is the biggest global race of Energy efficient vehicles organized splendidly. There are three continental editions of the race namely, African, American and Asian. In European- African edition over 200 teams take part annually with over 50,000 spectators. The vehicles are divided into different categories. There are two types of classes based on sizes i.e. small vehicles Protoype class and big vehicles UrbanConcept class. In each class there are different supply categories namely, petrol, alternative fuels, diesel, battery and hydrogen. Since 2012 the race has been held in the centers of big cities. European editions in the years 2012 to 2015 were held in Rotterdam and in 2016 will be held in London.

Fig. 1. Research vehicle HydroGENIUS [own study]

3. Characteristics of driving

The operation of a hydrogen fuel cell stack does not have the same efficiency for each parameter. Therefore, it is favorable to use the cell in constant working conditions. An electric vehicle has changeable energy demand due to variable speed of driving.

During a typical drive there are large changes in the power demand. These model changes in demand for energies are consciously planned in the SEM race. The plan of a race includes typical situations in city traffic [8]. In the course of moving from a standstill and accelerating, a large amount of energy from the power supply must be given. The vehicle reaches the target cruise speed in urban conditions and then during continuing the drive, demand for energy is low. Driving conditions and, in particular, bending and overtaking causes small changes in energy demand applicable to the necessary speed changes. With such small changes, there is great potential to use energy buffer for both short collection of energy for propulsion as well as charging the buffer through regenerative braking. During the stop the vehicle does not require supply and what is more energy from braking may be obtained in a very short period of time. The system generates significant energy at high power. The magnitude of braking power normally makes it difficult to recover all the braking energy during emergency braking. During a stop at a traffic light, for example, the demand is very low, and the power supply should be in a great readiness to accelerate smoothly and consume the appropriate amount of energy. It is possible to adjust the current operating parameters of the cell using a controller , but it is not as dynamic as the change of energy demand of the vehicle. From the point of view of operation of the cell, the most advantageous situation would be when the cell works under constant conditions, for maximum performance, regardless of the current energy demand of the vehicle. For that purpose the solutions are used which allow energy buffering, most frequently they are supercapacitors or batteries. During the increased demand for energy supercapacitors are discharged while during the reduced demand for energy they are recharged. As regards electric vehicles they are an essential part of the electrical system using hydrogen fuel cell stack. Supercapacitor battery also allows the optimal selection of the cell. The cell in this case is selected based on the average energy demand system, which is much lower than the maximum energy consumed by the vehicle. The power of the cell should be chosen with a certain excess. The lower cell power means lower costs of purchase and the reduction of its size and weight. An additional advantage of the use of supercapacitors is the possibility of energy recovery during braking. The simplest option is to use reverse operation of the motors. In this way the motor acts as a generator losing the mechanical energy that is converted into electricity. Supercapacitor batteries are used for the storage. During braking without energy recovery, most of the energy of the vehicle is lost. In energy-efficient solutions for electric vehicles due to the unfavorable energy balance this situation is unacceptable.

4. Hydrogen fuel cell stack

Principle of operation of hydrogen fuel cell stacks is similar, however their working parameters and characteristics are diverse. For this reason, the model of the system has been created for specific example, instead making a generalized numerical model. The research and the model has been done for the hydrogen fuel cell stack mounted in HydroGENIUS. This approach allows for subsequent verification of test results and also allows a more precise selection parameters of the numerical model. If needed, the model can be easily converted for parameters of different hydrogen fuel stack.

The fuel cell stack used in the vehicle is H-1000XP made by Horizon Fuel Cell Technologies company[3]. Nominal power of the fuel cell is 1000W, the temporary peak power can reach 1200 W. The hydrogen fuel cell is supplied by 99% pure hydrogen. The pressure of hydrogen is 0,5 bar and is constant. The oxygen required for the reaction is drawn from the atmospheric air. The fuel cell stack is equipped with fans with variable speed control, used for increasing the air flow through the cell. The characteristic of the fuel cell stack is shown below (Fig. 2).

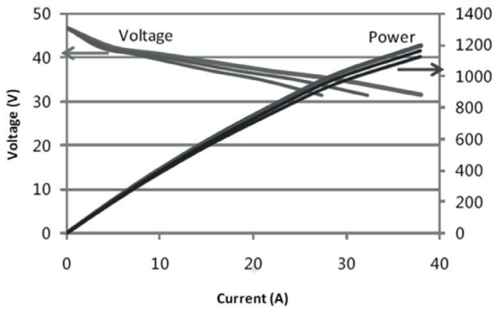

Fig. 2. The characteristic of the fuel cell stack [own study]

Hydrogen consumption increases with the increase of fuel cell stack power, however it is not a linear correlation. Efficiency of the cell varies depending on the power of the cell. The efficiency is the key for vehicle hydrogen consumption and thus critical for its driving range. The dependence of the efficiency and the power has been calculated, based on hydrogen consumption of the fuel cell stack. It has been shown below (Fig. 3). The maximum efficiency is 54,7% for the power 524 W. The efficiency for the values lower and higher then 524 W is lower, especially for values from the range 0- 200 W. The efficiency for the nominal power 1000 W is 47,9 %.

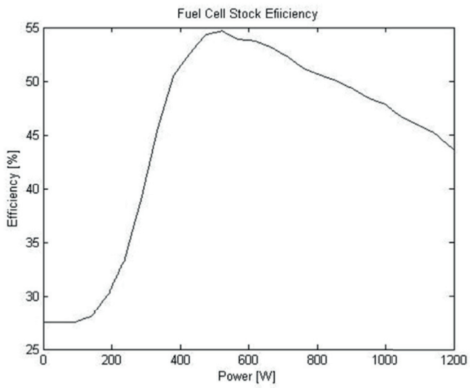

Fig. 3. The efficiency of the hydrogen fuel cell stack [own study]

5. The numerical model

The issue of hydrogen fuel cell stack control is a complex problem. In particular, the selection of such control parameters to get the required power with minimum hydrogen consumption through the fuel cell stack. It is a problem of optimal control. Because the system is complex and the many parameters intricate, has been decided to build a numerical model of the hydrogen power cell with the motor.

The model has been prepared in Simulink package of Matlab application. It consist of for main blocks: fuel cell stock block, engine block, supercapacitor block and the control block. Additionally, in the model has been used single basic blocks to provide correct signal flow. To create a block the fuel cell stack, the characteristics has been used, not going into details of its working. For the proper modeling of hydrogen fuel cell it is enough detailed. It also simplifies the model. The supercapacitor block is responsible for simulating supercapacitors installed in the vehicle, primarily for simulation of its charging and discharging. The engine block is a block responsible for the power demand of the system. The power demand for the model is variable like for a car. At the moment the engine block is only a block responsible only for power demand, the full simulation of the electric engine will be added in the future. The control block will be responsible for the optimal control of the fuel cell stack. At that moment the block limits the maximum power of the fuel cell stack. All simulations has been performed for the fixed step size 0,1 s.

5.1. The energy consumption assumed for the system

One of the most important uncertainty in model is the car energy demand. It is very variable because of the working conditions of the car. During the stop, the energy consumption is very low, and when moving off very high. Because it is not possible to accurately determine the energy demand changes, the task to determine a route profile that would be and reliable and allows for comparing the results of the simulation, is a very difficult issue. Energy demand in the conditions of urban traffic is quite different than during driving on the highway. For the purposes presented here preliminary calculations a hypothetical waveform energy requirements of the system has been assumed for the simulations. The waveform has been shown in the figure below (Fig. 4). In the waveform occur fragments of stop, moving off and slow driving. The duration of the simulation is only 10 minutes, to decrease the time of preliminary calculations.

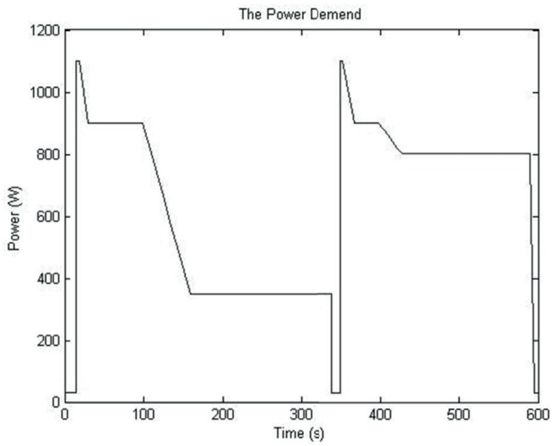

Fig. 4. The system power request [own study]

5.2. Selecting the supercapacitors batery

The battery of supercapacitors play an important role of the energy storage in the system. It's essential part of the system equipped with a hydrogen cell stack. In the case of low energy consumption the battery of supercapacitors are recharged. Because the maximum peak power of electric engine is much higher than maximum peak power of the fuel cell stack, it is necessary that the supercapacitors always have to be charged to some level. The most important criterion of selection a supercapacitors for the system is their capacity. The value of capacity must be optimal. Too low capacity of the supercapacitors will decrease their effectiveness and results, that they will not be able to compensate a temporary deficit of energy in the system. Too high capacity will result in too long a time of initial charging and increase the cost of the system. The maximal voltage in system should be lower than maximum allowed voltage for the battery of supercapacitors. Series of simulations has been performed for the hypothetical energy demand, in order to select optimal capacity of the supercapacitors. The capacity of the capacitors should be selected so as to maximize the efficiency of the hydrogen fuel cell stack. For the purposes of simulation, has assumed a fixed resistance value connected in series with the supercapacitor as 1Ω. The real value of resistance should be selected after chosen a particular model of the supercapacitors. Has been assumed, that during the initial charging, the efficiency of the fuel cell stack should be maximal. Therefore, during the first 15 seconds of the simulation the maximum power of the fuel cell stock was limited to 550 W, and during the rest of the simulation has assumed maximum power as nominal power- 1000 W. The results for different capacity of the supercapacitors is shown in figure 5.

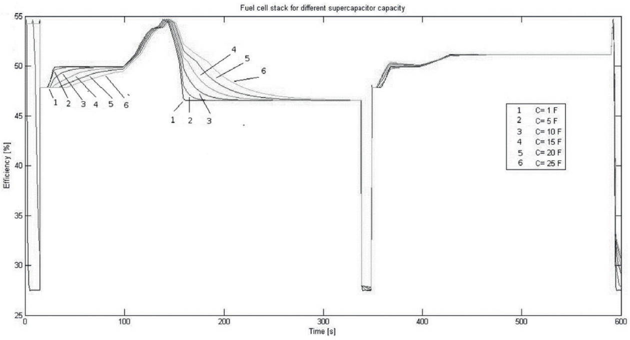

Fig. 5. The efficiency for different supercapacitor capacity [own study]

The analysis of the efficiency of the fuel cell stack for different values of the capacity shows, that using the supercapacitor with high capacity is more benefit than with the low capacity. The mean efficiency of the fuel cell stack increase with the supercapacitors capacity increase. However, simultaneously with increasing the capacity of supercapacitors, time of the initial charging is rapidly growing. For the example above, the maximum capacity of the supercapacitor, for that the charging level is sufficient is 8 F. This capacity has been selected. The result of the simulation for 8 F capacity has been shown below. The resulting actual energy supplied to the system is very similar to the energy demand in the system. The capacity 8 F is optimal for this system.

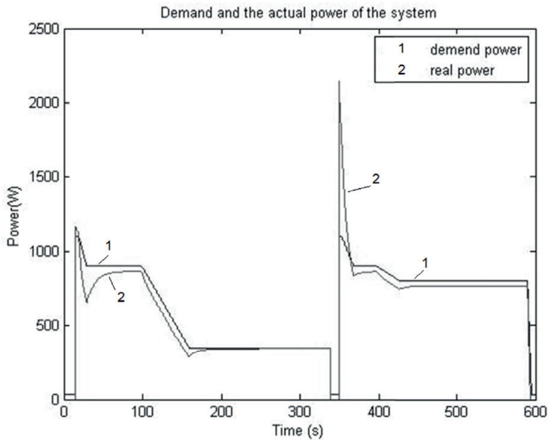

Fig. 6. The simulation for capacity of 8 F [own study]

6. Fuel cell stack control

The control of the fuel cell stack should be optimal. In this case, the control should provide the required amount of energy while simultaneously a low amount of consumed hydrogen. Therefore the fuel cell stack should work with relatively high efficiency. If high efficiency is not possible to achieve, the fuel cell stack should work with minimum request power, so as to ensure minimum consumption of hydrogen. In practice, the control of the fuel cell stack it is possible to realize only by limiting the maximum power of the hydrogen cell, by reducing the supplied amount of hydrogen and air. The control in this case is to smooth change of this parameter. By temporarily reducing the maximum power of the fuel cell stack to the minimum, necessary for the cells working, it is possible to control the launch time of the fuel cell stack. Because of the low efficiency of the fuel cell stacks for the low power, the strategy of the control should provide using the hydrogen fuel cell stack only for high power. Therefore more benefit is that for low energy request, the fuel cell stack should work intermittently with the higher power and the higher efficiency, than continuously with the low power minimal necessary power. In case when the energy consumption would be low, the energy should come only from the supercapacitors, which should be periodically charged.

7. Conclusion

An important part of the general control system applied to an electric car with a hydrogen fuel cell stack is control system for the hydrogen fuel cell stack. Proper generation of electricity in combination with buffering energy gives great potential for reducing energy consumption. For proper planning control process of hydrogen fuel cell stack it is necessary to obtain knowledge about the cell operation and optimization of the internal system processes. For the purposes of the numerical optimization of the process of generating electricity from the fuel cell for the purpose of driving an electric car numerical simulation model has been built. The model includes not only a model of hydrogen fuel cell stack with the regulatory controls, but also the energy buffer largely decisive for the proper operation of the system. The paper describes in detail the character of this model. Numerical simulation model permits the optimization of the control strategy of the cell according to the driving conditions as well as to determine the optimal design parameters cell itself and above all a buffer in the form of a set of super capacitors. In the future steps it is planned to integrate the simulation model of the hydrogen fuel cell stack electric supply with the simulation model of the entire vehicle.

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