The Efficiency of a Hydrogen Circuit in a Smart Grid

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Abstract— The paper describes the connection of a hydrogen circuit to a 24 V experimental smart grid. The principle of the proposed design consists in improving the stability of the current grid and enabling maximum exploitation of the electric energy produced by renewable sources (micro-hydropower plant, photovoltaics, and wind power plants). In this respect, the authors present a very important module to save the energy and show an efficiency calculation of the hydrogen circuit.

1. INTRODUCTION

This paper deals with an idea of smart grid, a physical realization of a DC smart grid laboratory model and a strategy of its control. An authors' idea is to utilize a maximum of renewable energy [1, 2]. It would be a logical and the most economical principle, but it is in a contradiction with physical principles of electrical energy, with requirements coming from consumers and with possibilities of an electrical distribution system and information and control systems. A saving electrical energy is a difficult problem [3].

A principle of a hydrogen management is usage of hydrogen as an energy carrier and storage. The hydrogen can be used to power e-cars as well as heating, but also for a preservation of electricity in the fuel cell. For hydrogen sources utilized in the hydrogen management, there are several basic solutions. The actual technology of hydrogen electricity has several variants [4]. The goal of this paper is to measure and calculate efficiency of hydrogen circuit.

2. EXPERIMENTAL ELECTRICAL NETWORK (E.E.N.) DESCRIPTION

The authors specify most of existing possibilities of the electrical energy saving. In this chapter authors describe a smart grid and design a physical realization of the DC smart grid with saving into different technologies [2]. And one of these ways is hydrogen. For our experiments in smart grid we use energy storages as accumulators and metal hydride storage. Energy for the smart grid is obtained from the power plants.

Small power plants utilizing renewable energy sources are connected to our E.E.N. Firstly, there is a PV panel and small wind power plant which are situated on a roof of the building. The micro-hydropower plant must be placed in other locations from practical reasons. A produced energy is stored in batteries and in the hydrogen container.

The control system, including the CompactRIO hardware and LabView software, manages the flow of energy in individual sources and performs the consumption control. This system can determine which resources are currently supplying the power to the grid and what amount of power is being delivered.

The designed E.E.N. is equipped with a number of batteries for each individual power source; however, the introduction of centralized battery storage is proposed. Although the storage of electric energy in the form of hydrogen does not seem to be a promising approach, a hydrogen fuel cell (one metal-hydride container as a form of hydrogen storage) will be integrated into the E.E.N. in order to realize a source of peak energy.

3. E.E.N. — STORAGES

An idea is to utilize a maximum of renewable energy which is available in an every moment. It would be a logical and the most economical principle, but it is in a contradiction with physical principles of electrical energy, with requirements coming from consumers and with possibilities of an electrical distribution system and information and control systems. A saving electrical energy is a difficult problem. In the contribution authors specify most of existing possibilities of the electrical energy saving. In our E.E.N. we use two types of storages. The first type contains accumulators (auto batteries), see Fig. 1(a)) and the second type represents a metal hydride storage tank, see Fig. 1(b)).

Accumulators — The first type of storages contains accumulators. We use battery VARTA in our smart grid.

Hydrogen storage — The second type of storage is hydrogen storage. A metal hydride storage tank consists of special metal alloys that have to capability of storing hydrogen atoms in their crystal lattice. In order to obtain as large a surface area as possible for this, the metal alloys are pulverised. The hydrogen is introduced into the storage tank under slight positive pressure, and reacts with the metal alloy to form the metal hydride. This process is exothermic, i.e., heat is dissipated. Heat must be reintroduced in order to discharge hydrogen from the storage tank. Metal hydride storage tanks have a high storage density with respect to the volume. However, they have a low storage density with respect to the weight. New, lighter storage materials are being developed. The use of these lighter materials could lead to a considerable improvement of weight-related storage density [5, 6].

(a) (b)

Figure 1: (a) The accumulator VARTA heavy duty 12 V–140 Ah. (b) The Ovonic^{TM} solid hydrogen storage canisters 760 sl.

4. HYDROGEN CIRCUIT

In an E.E.N., a hydrogen circuit is applied in situations when all the accumulators are fully charged and the smart grid exhibits an energy surplus (meaning that the related photovoltaic panels, wind power plants, or small hydroelectric plants generate energy constantly). Such a surplus is then used to produce hydrogen, and this product is stored in a metal hydride storage case.

In our case, for our experiments we use a small hydrogen circuit contains of a metal hydride canister see Fig. 4. This hydrogen circuit can be divided into three main parts. The first is electrolyser (hydrogen generator) with a dryer and purifier, the second part is the storage, in our case the storage is a metal hydride storage tank with a valve system to switch between a charge operation and consumption, and the third one is a fuel cell.

Electrolyser = hydrogen generator — In electrolysis, chemical compounds are decomposed by electrical current. For example, electrolysis can be used to decompose water into its constituents: hydrogen and oxygen. In principle, an electrolyser consists of a negatively charged cathode, to which the positive ions migrate; second a positively charged anode, to which the negative ions migrate and third, an electrolyte, a material which conducts due to ion migration [7].

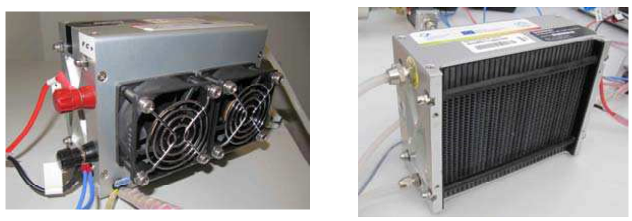
We use an electrolysers ACTA EL100c+dryer hydrogen generator, see Fig. 2. Technical specification of EL100c: Max hydrogen flow rate @20°C/1 bar: 100 Nl/h, max out pressure: 30 bar, Purity of hydrogen: 99.95% @30 bar, maximal power consumption 700 W, max water consumption: 0.1 l/h [8].

Figure 2: The hydrogen generator ACTA EL100c + dryer.

Metal hydride canister — We use an OvonicTM metal hydride storage tank (see Fig. 2) with these parameters: Hydrogen content: 850 liters and fill to: 6706.1 gram [10].

Fuel cell — The fuel cell's principle of operation is the reverse of that of an electrolytic cell (electrolyser). Like the electrolytic cell, a fuel cell consists of a negative and positive electrode and an electrolyte. We use Proton Exchange Membrane Fuel Cell (PEMFC). The PEM fuel cell converts chemical energy into electrical energy efficiently. The electrolyte is a thin proton-conducting polymer membrane. The membrane is coated with catalyst material on both sides. These two layers form the cathode and the anode of the fuel cell. Individual cells are connected together to form Compaq stacks in order to match different power requirement. Stack ability high efficiency, and good cold-start behavior of the PEM fuel cell make it suitable for a wide range of applications, e.g., for electric drivers in cars, as a replacement for disposable and rechargeable batteries, and for residential electricity production [6, 7].

We use H-200 Fuel cell Stack by Horizon Fuel Cell Technologies, see Fig. 3. The fuel cell has these parameters: rated power 200 W, performance: 28.8 V @7.2 A number of cells: 48.



(a) (b)

Figure 3: H-200 fuel cell stack by horizon fuel cell technologies (left and right side).

The arrangement of the hydrogen laboratory is outlined within the block diagram and image shown in Fig. 4. The entire hydrogen circuit can be controlled from LabView, via a signal sent by the E.E.N.-driving program. If an energy surplus is detected, the program will send a signal to activate the controlled switch; thus, the electrolyser and dryer will start to operate. The electrolyser is capable of producing very clean (with 99.95% purity) dry hydrogen at @30 bar. Such a high pressure has to be decreased to the value of 10 bar by means of a manual reduction valve; the reduced pressure is applied to fill the hydrogen storage, which is formed by a metal hydride canister.

In an opposite state occurs in the E.E.N., namely a condition when the local accumulators are discharged and only an insufficient amount of energy is available in the network, LabView dispatches a signal to open the controlled valve 2; through the open valve, hydrogen will be transported from the metal hydride storage to the fuel cell. The hydrogen pressure, however, has to be maintained at 0.45 bar; otherwise, the cell could be destroyed. Further, it is also possible to utilize a flowmeter to determine the quantity of hydrogen flowing from the metal hydride storage. The fuel cell, too, is switched on by a signal because its actual start needs to be performed in the no-load mode; only after approximately 10 seconds, the controlled DC/DC converter is connected. The converter regulates the amount of current flowing from the fuel cell, thus facilitating optimal operation of the cell.

5. EXPERIMENT: EFFICIENCY OF HYDROGEN CIRCUIT

Chapter 4 describes the hydrogen circuit embedded in the E.E.N. In this context, a very important problem consists in the energy efficiency of the circuit; the efficiency indicates the portion of the input energy E_{input} dissipated in the system as the actual usable energy E_{usable}.

$$\eta_{\text{energy}} = \frac{E_{\text{input}}}{E_{\text{usable}}}. \tag{1}$$

To calculate the energy efficiency, we applied the law of conservation of energy, given the starting condition where the metal hydride storage was filled with hydrogen at 3.31 bar and the ambient temperature of 22°C.

At this point, we activated the electrolyser and let it work until the pressure in the vessel increased to 10 bars; this condition was reached after 150 minutes of operation, and the vessel temperature had risen to 35.8°C within the period. Having stabilized the vessel temperature at 22°C, we found the related pressure to be 5.77 bars. Given that the vessel temperature was

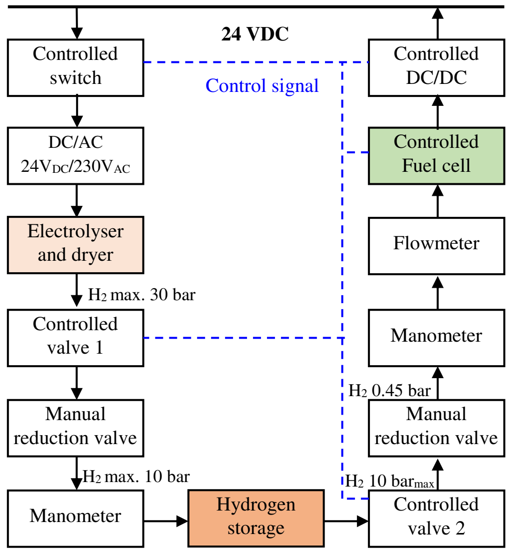


Figure 4: Hydrogen circuit.

maintained at 22°C, the pressure increased by 2.46 bars, and this increase necessitated the value of $E_{\text{input}} = 1672\,\text{W/h}$.

To obtain the energy value E usable, we switched the fuel cell on and measured the volume of energy supplied to the 24 V grid. The measurement was not stopped until the vessel pressure reached 3.31 bars at 22°C; we thus obtained the value of $E_{\text{usable}} = 266.47\,\text{W/h}$, and substitution of the energy values E_{input} and E_{usable} in Eq. (1) yielded the hydrogen circuit efficiency energy = 15.94%.

6. CONCLUSION

This contribution presented a calculation of the efficiency of a hydrogen circuit in an E.E.N. To perform the actual calculation, we first needed to acquire the values of energy entering and leaving the hydrogen circuit — E_{input} and E_{usable}, respectively. During the measurement, the major precondition was to maintain the metal hydride storage at a constant temperature. The input energy into the hydrogen circuit, E_{input}, was established to be 1672 W/h, and the vessel pressure increased by 2.46 bars at 22°C. The measurement of the output energy of the hydrogen circuit remained in progress until the vessel pressure dropped to 3.31 bars at 22°C; we thus obtained the energy value of $E_{\text{usable}} = 266.47\,\text{W/h}$. The resulting efficiency of the hydrogen circuit can therefore be expressed in the amount of 15.94 %. The measurement cycles pointed to significant dependence of the pressure in the metal hydrid storage on the ambient temperature.

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