Development method of Hybrid Energy Storage System, including PEM fuel cell and a battery

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Abstract. Development of fuel cell (FC) and hydrogen metal-hydride storage (MH) technologies continuously demonstrate higher efficiency rates and higher safety, as hydrogen is stored at low pressures of about 2 bar in a bounded state. A combination of a FC/MH system with an electrolyser, powered with a renewable source, allows creation of an almost fully autonomous power system, which could potentially replace a diesel-generator as a back-up power supply. However, the system must be extended with an electro-chemical battery to start-up the FC and compensate the electric load when FC fails to deliver the necessary power.

Present paper delivers the results of experimental and theoretical investigation of a hybrid energy system, including a proton exchange membrane (PEM) FC, MH-accumulator and an electro-chemical battery, development methodology for such systems and the modelling of different battery types, using hardware-in-the-loop approach. The economic efficiency of the proposed solution is discussed using an example of power supply of a real town of Batamai in Russia.

1. Introduction

More than 900 settlements in Russia are not connected to the centralized grid. These settlements are powered up by diesel engines built in the last century. The cost of one kWh is high due to diesel fuel transportation costs, which occurs normally only in winter period, as there are no roads except for winter trails upon frozen rivers, and low efficiency rate of these engines. It is needed 30 times more Russian rubles to generate 1 kWh than the average in Russia, and this price difference is fully subsidized from the state budget. The need for sustainable energy in these areas is estimated at about 2,54 bln kWh per year [1]. Typical daily load of a small town (Fig.1) from this area has been studied in order to identify the peak consumption for the periods of maximum load.
According to the solar energy potential map, most of the decentralized areas have 3.5 to 4.5 kWh per m²/day [3]. One of possible solutions to reduce the kWh price, generated from diesel fuel, could be replacing the diesel engines with autonomous power generation systems that include solar panels and energy storage systems.

First solar panel systems installed in Batamai town has worked for one year producing 30 kWh, resulting in saving of 11 tons of diesel [4]. However, during the night hours diesel engines had to continue working. If an energy storage systems would be installed together with solar panels, the higher diesel engine replacement percentage could be achieved. Unlike conventional hydrogen storage systems, keeping the gas under extremely high pressures of several hundreds of bars, the metal hydride storage keeps it in a bounded form at pressures of about 2 bar [5, 6]. Simple thermal management of the MH-accumulator using cold and hot water allows regulating the intensity of adsorption and desorption of the gas from/into MH, regulating the mass flow rate through the FC.

Low power hybrid energy storage system with PEM fuel cell, MH-storage and a lead acid battery was designed and tested in present work. Experimental results of the hybrid energy storage system functioning are in the paper. Lead acid battery was chosen in order to lower the costs of the system, while other types of batteries were tested theoretically using the hardware-in-the-loop approach in frameworks of the developed methodology and selection criteria.

2. Experimental set-up

2.1. Experimental set-up and procedure
The general view of the setup, employed in experiments, is depicted in Fig. 2. Hydrogen from a middle pressure storage tank (15-30 bar) was supplied either directly to the fuel cell or to the metal hydride reactor for further storage (Fig. 3). PEM fuel cell with maximum power of 175 W was connected to the lead acid battery and the electric load, which was emulated using ten 20 W LED-lights and 2 W ventilator for cooling, with the corresponding total load of 202 W. The standard 12 V lead acid battery, which initially powers up the fuel cell and helps meeting the load demand whenever fuel cell can’t, as its power of 175 W was lower the total load of 202 W. When the load is below 175 W, the FC provides power both for the load and the battery, charging the latter one.
Metal hydride storage is a low pressure storage that is able to take hydrogen both from pure H\textsubscript{2} and from a mixture of gases [5-7], acting additionally as a filter. In order to take H\textsubscript{2}, metal hydride needs to have the heat dissipated from the reactor, which is done by the water cooling system. When FC needs hydrogen, stored in MH, it can be fed into it, passing the hot water through the reactor, intensifying the desorption of hydrogen from the MH. Depending on the need of experiment or availability of hydrogen, it could be supplied into the FC from a storage tank or MH-reactor.

The fuel cell, the battery and the load joint functioning was investigated in the experiments, measuring thermal and electrical parameters of the setup. Following quantities were measured:

- Current on the load, A
- Power of the load, W
- Current on the battery, A
- Power of the fuel cell, W

Current on the load was changed throughout the experiment. Power of the load has been calculated. Power of the fuel cell was measured in order to see whether it meets the load demand or not. It also helped to see the fuel cell shut downs. Current profile on the battery is present below. In the second part of the paper these current profiles were integrated to the simulation set-up where 3 other types of the batteries were investigated under the same load profiles.

All measurements were taken by NI-PXI where physical measurements were transformed to the analogous signals. The process of measurements’ representation has been automated using LabView, and instantaneous values were logged into a file for further processing. Measuring uncertainties of the quantities are estimated as follows: for current on load – 0,1%, for power on load – 0,05%, for current on the battery – 0,09%, for power of the cell – 0,1% [7].
Figures 4-6 depict typical profiles of current on load, observed in experiments.

Fig 4. Typical working mode of the battery

Fig 5. Optimal working mode of the battery

Fig 6. Critical working mode of the battery

It was noted that 4 working modes of the fuel cell repeat one after another. These working modes represented the start of the system, an optimal performance stage and some of the most common fuel cell shut downs. The current curves above represent the real load profile data that battery meets while working with the fuel cell.

**Mode 1 - start of the fuel cell system** - it was noted that normal fuel cell start procedure takes 3 initial starts of the FC. It happens due to the FC trying to heat it up on its own performing chemical reactions one after another. Batteries on the figures 4 and 6 experienced fuel cell start-up procedures with three repeated peaks from -2 to 5 A.

**Mode 2 - working mode of the fuel cell** meeting the load demand and charging the battery - ideal working mode of the fuel cell. Figures 4 and 6 show this type of FC load starting from the 30th
minute of the experiment when optimal working mode of the battery (Fig.5) experiences this type of load for most of the time.

**Mode 3** - unexpected **fuel cell shut down** due to the **low income hydrogen pressure** - in order to overcome this problem we have installed a hydrogen receiver right in front of the FC. It collects hydrogen and meets the pressure demand of the FC. However, the battery needs to meet this rapid demand peak and work in the critical mode (Fig.6).

**Mode 4** - immediate **high power demand** that fuel cell can’t meet - it was noted that FC needs some time to adjust to the raise of demand power. in order to overcome this problem we started to give few minutes for the FC to adjust its power output to the demand before we rose the load power again. The battery again works in the critical mode (Fig.6).

This load data was integrated to the Triphase inverter controller model to take the current out of the Regatron battery emulator in order to test different types of the batteries and create an experimental methodology for choosing the battery to work with other hybrid ES systems (such as fuel cell in this particular case).

### 3. Battery system design state-of-the-art

Battery system design consists of 6 steps: defining battery parameters, calculating discharge current, conductor size, short circuit current, selecting protection devices and implementing the whole battery system assembly [9]. However, the first step of defining battery size and battery type has high level of uncertainty. It depends on the hybrid system components, overall system requirements, weather conditions, etc. For the case of Batamai village lead acid battery was chosen. However, similar case described in the literature [10] presented different choice of the battery type for the same weather conditions and similar performance criteria.

There are four commonly used mature battery technologies [11]: economically viable Lead Acid with low specific energy and limited number of cycles, mature Nickel-cadmium with ability to work in extreme temperatures and environmental concerns, mid-toxic Nickel-metal-hydride with high energy density but quick self-discharge rate and expensive Lithium-ion with high number of cycles and low maintenance [11]. All four types are used in different fuel cell systems [12], autonomous power generation equipment included [13], however a strong methodology of choosing the right type of battery is not defined.

Due to high cost of physical testing equipment, modeling approach proved to be a reliable source. There are economic and “cost-of-use” models [13] that take into consideration one criteria. Tremblay et al [14] highlighted three types of battery models: electrochemical, experimental and electrical [15,16] and emphasized that electrical characteristics of the battery are enough to use it in the system design. The field of battery modeling has improved by introducing mathematical models with probability [17] and Thevenin models [18].

Tremblay-Dessaint model [14] has been developed further into physical battery emulator that can produce the output voltage of different battery types. A controllable load has been added to the system in order to create a physical battery testing set-up.

### 4. Methodology

The experimental set-up (Fig.7) consists of battery emulator and battery controller. One can think of the whole system as a bidirectional AC/DC/AC converter. The Regatron rectifier's control system is
coupled with mathematical models by Tremblay and Dessaint [14] of different batteries. The BatSim controller receives several input parameters: battery type, its state of charge and battery model data in order to calculate desired voltage reference on the DC-link and then set that voltage using feed-forward decoupling control. Combined together, these three components: rectifier, controller and math model, allow us to simulate performance of any battery as seen from the DC-link.

The Triphase inverter and controller act as battery current control system. The system accepts current output reference as a parameter and then sets it to the desired value. Finally, the whole system is now capable to emulate any battery, provided we have a proper mathematical model. It is important to note, that not only we can model charge or discharge currents, but also the terminal voltage change according to the batteries SOC.

The set-up consists of battery emulator and Triphase AC/DC inverter (Fig. 8).

4.1.1. Battery Emulator. In order to emulate 4 different types of the batteries (NiMH, NiCd, Li-ion, Lead acid) Regatron TC.GSS hardware was used. Regatron GSS is physically an AC/DC converter. It
has a script based performance and gives the output voltage according to the Olivier Tremblay and
Louis-A. Dessaint mathematical model.
The flow of the current is controlled to/from the simulated battery using Triphase model in Matlab.

4.1.2. Control. Bottom-layer control. Power converter model. AC/DC power converter has two
objectives. 1. Control DC bus voltage and form 3-phase AC voltage vectors to correspond to required
currents. The model uses 3-phase to d-q coordinates transformation. While \( I_q \) represents reactive
current component and can be controlled directly, \( I_d \) component is calculated in order to maintain DC
bus voltage. 2. DC/DC converter aims to control DC current charging/discharging the battery
connected to DC side. The model allows setting this current value in Amperes and current flow
direction (to or from battery). Flowing from battery DC current formed by DC part of converter model
charges the DC bus. The AC part of the model calculates \( I_d \) component for the AC current and forms
the corresponding AC voltage in order to create AC currents that will discharge DC bus capacitor and
maintain it on required level.

4.1.3. Integrated current control model has been added to the Triphase control scheme.

4.1.4. Hardware-in-the-loop tests experimental set-up.
Battery emulator Regatron GSS is being powered from AC university grid, it is then connected with
DC side of the triphase DC/AC converter. The flow of energy goes to the AC side of the Triphase
converting battery voltage (ranging from 10 to 70V) to the 600V that is sent back to the University
grid.

The flow of the current is controlled to/from the simulated battery using Triphase model in Matlab.
The model that controls the current drawn from the battery is integrated to the Simulink model of
the Triphase (Fig.9). Current curves represent real load profile that battery meets while working
with the fuel cell.

Li-ion battery was initially charged to 80% state of charge. The model had 15 cells in series and 15
cells in parallel. NiMH battery was initially charged to 80% state of charge. The model had 30 cells
in series and 5 cells in parallel. NiCd battery was initially charged to 80% state of charge. The
model had 30 cells in series and 15 cells in parallel. Lead-acid battery was initially charged to 80%
state of charge. The model had 30 cells in series and 4 cells in parallel.
5. Results

Comparative analysis of different types of the batteries was based the following criteria:

- Rapid discharge regime. Fuel cell temporary fault.

Looking at the state of charge (SOC) graphs during the rapid current change spots one could see how fast and how deep the graph decreased. Since all the batteries had almost the same capacity, the change on the graph would determine the battery with the highest rated power among all 4. We need a high power performance for the battery to make sure that the fuel cell shut downs will not affect the load.

- Rapid charge regime. Fuel cell charging the battery after getting back to the normal operating condition

When the fuel cell gets back online the battery needs to charge quickly. The battery needs to be ready for another shut down as quickly as possible. The slope of a tangent line to the SOC graph during the battery charging mode was used.

Li-ion and Lead Acid batteries are the best choices according to the criteria specified. Despite the fact that Li-ion battery charged faster, it is not enough to state that Li-ion battery should be finally chosen as the battery for the system. The difference is insignificant. More criteria are now being developed.
Regardless the fact that the work on the criteria is ongoing, testing method can already be used for other cases, where many types of the batteries need to be compared.

6. Conclusion
Battery use in the Hybrid Energy Storage system together with fuel cell was studied and tested in real experimental grid. Four types of batteries were carefully compared. It is evident that Li-ion and Lead Acid batteries stand out and meet the criteria specified. However, the difference between two types is not obvious. Thus the current work is focused on deeper understanding of the system requirements. It will also help specify the criteria for a bigger system development.

Regardless the absence of one clear choice the new experimental method can be used for other systems. The usage of battery emulator and hardware-in-the-loop tests makes it possible to compare the performance of all battery types in the “close to real” physical condition. Proposed methodology helps to choose the battery type suitable for each specific case.

As further research, battery electrochemical parameters (degradation and memory effect) can be modeled and programmed into the battery emulator. Moreover, a 2 kW autonomous power generation system based on hybrid energy storage and electrolyzer is at the stage of design and development. The result of this work will help to choose the battery type for the new system. More hybrid energy storage performance tests and experiments will be conducted in order to find the best solution for that system. This prototype will be tested in the field and in the smart microgrid environment of Skoltech Energy Systems Lab.

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