Hydrogen-oxygen steam generator applications for increasing the efficiency, maneuverability and reliability of power production

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Abstract. The comparative feasibility study of the energy storage technologies showed good applicability of hydrogen-oxygen steam generators (HOSG) based energy storage systems with large-scale hydrogen production. The developed scheme solutions for the use of HOSGs for thermal power (TPP) and nuclear power plants (NPP), and the feasibility analysis that have been carried out have shown that their use makes it possible to increase the maneuverability of steam turbines and provide backup power supply in the event of failure of the main steam generating equipment. The main design solutions for the integration of hydrogen-oxygen steam generators into the main power equipment of TPPs and NPPs, as well as their optimal operation modes, are considered.

1. Introduction

The transition in modern energy to the use of more efficient power plants, for example combined-cycle power plants, as well as the growth of the share of renewable energy sources in the total power generation, causes the necessity to develop reliable and efficient energy storage technologies for the balancing of power generation and consumption schedules. The use of hydrogen as the energy carrier is one of the solutions. For the big amounts of hydrogen at present the power-to-gas technology is offered. The alternative way of power generation from hydrogen is direct combustion of hydrogen in oxygen, both being the products of water electrolysis, in specially designed hydrogen/oxygen steam generators, with the further use of the produced steam in steam turbine cycle.

HOSG technology of hydrogen combustion in oxygen in order to obtain high temperature steam is implemented in equipment with high specific power and the absence of hazardous emissions. High rate of the processes (hydrogen combustion, heat transfer, component mixing etc) ensures minimal start-up duration, which is important especially at use of this technology for back-up power. The idea of HOSG was initially offered in the works of IVTAN and DLR [1-3] as an additional energy storage unit at TPP for peak power coverage.

The first experimental samples of MW-scale HOSG were developed in Germany (DLR aerospace center) and in Russia (IVTAN, «Keldysh Center», Khimavtomatika JSC) [4-6]. These companies also developed and tested kW-scale units. The process investigations and HOSG development later was carried out in Japan within WE-NET program [7]. At present the demonstration level HOSG units are developed and tested by JIHT RAS (former IVTAN) in cooperation with Khimavtomatika JSC in Russia. Further development of HOSG technology gave the basis for the development of hydrogen energy storage systems for grids, steam superheaters at TPPs, NPPs and geothermal plants with the goal of their maneuverability increase and also for autonomous fire extinguishing systems [8-10].
2. Dynamic features of HOSG
The results of experimental investigations [4, 11] show good stability of operation of experimental HOSG with 25 MW thermal capacity. Together with this the steam generation process was featured by high efficiency and low content of unburned components at the outlet thus giving the basis for the development and manufacturing of semi-commercial sample of HOSG for various power engineering applications.

Typical time evolution of temperature and pressure at test of HOSG is shown in figure 1. The startup of HOSG and reaching the nominal regime of 23 - 25 MW at “soft” startup is split in three stages.

- from 0 to 4th second the ignition unit starts with warming up of the combustion chamber up to 600-700 K. The system of startup regime cooling starts from second 2 and temperature falls down to 325 K;
- from the 4th second the starting flows of hydrogen and oxygen are fed increasing the temperature of the produced steam up to 500-550 K. The warm-up and diagnostics of the main indicating is carried out;
- from the 6th second the main flows of hydrogen, oxygen and water are fed into HOSG and up-to seconds 8-10 the temperature is increased up to the required and HOSG reaches the nominal power of 23-25 MW.

![Figure 1. Typical time evolution of temperature and pressure of the steam generated by HOSG: 1 – temperature in mixing chamber center; 2 – temperature in 5 mm from the inner wall of the mixing chamber, 3 – steam pressure in the mixing chamber, 4 – steam pressure in combustion chamber.](image)

It is shown that the total time of the HOSG reaching the nominal capacity at start is less than 10 seconds. It is worth mentioning that research by DLR [5] showed the possibility to avoid startup regime and total time of reaching the nominal capacity could be shorten down to 4-7 seconds. Such kind of the startup dynamics demonstrated by HOSG gives the wide field of applications of the technology for back-up or emergency power sources.
3. Evaluation of the possibility to increase the efficiency and maneuverability of power production at TPP and NPP

For the increase of the efficiency and maneuverability of power production equipment of TPP and NPP the following main features of HOSG are used: short starting period and high temperature of the generated steam which being mixed with the main actuating medium increases its temperature and thus the capacity of the plant several times faster than in traditional way. Thermodynamic and feasibility aspects of the creation of such systems are discussed in numerous publications [2, 6, 7]. In this case hydrogen and oxygen are produced by electrolysis at off-peak, stored and then used in high-pressure HOSG for the additional steam production and superheat. The obtained steam is fed to plant steam generator increasing its capacity in 10-12% which is allowed by the existing types of the turbine units of the power plants. Additional steam superheat is obtained by mixing the stoichiometric hydrogen and oxygen combustion products with the main flow of steam from TPP or NPP steam generator on its way to turbine (figure 2). Variation of the hydrogen (H2) and oxygen (O2) storage volume can lead to the use of the proposed scheme for the energy storage.

**Figure 2.** The scheme of hydrogen electric energy storage at steam cycle power plant: G – generator, EL – electrolyzer, ST – steam turbine, H2 – hydrogen storage, O2 – oxygen storage

Below is the calculation of energy storage system for 1000 MW TPP with 600 MWh of energy stored in hydrogen and additional power due to HOSG switching on accounting for 10% of nominal (100 MW), which corresponds to real aspirations of TPPs and NPPs for peak load and energy storage [6].

The estimation of hydrogen energy storage systems was conducted according the following method.

1) Capital cost of installed capacity of energy storage system HOSG

\[ S_{in} = N_{ac} \cdot C_{HOSG} \]  

here \( N_{ac} \) – installed capacity of energy storage system, kW; \( C_{HOSG} \) – specific cost of installed capacity of HOSG, $/kW.

2) The cost of electrolyser at operation during night off-peak from 23:00 to 07:00

\[ S_{el} = E_{el} \cdot C_{el}/8 \]  

here \( E_{el} \) – capacity of the storage system, kWh; \( C_{el} \) – specific cost of electrolysis equipment, $/kWh.

3) The cost of hydrogen and oxygen storage system
\[ S_{st} = E_{st} \cdot C_{st} \]  
(3)

where \( C_{st} \) is specific cost of hydrogen and oxygen storage, $/kWh.

4) Total cost of energy storage system

\[ S = S_{HOSG} + S_{el} + S_{st} \]  
(4)

5) The total cost of ownership of HOSG-based energy storage system of TPP

\[ TCO=\left(S+\frac{S_{op} \cdot T}{E_{st}} \cdot T \cdot 365 \cdot K_r\right) \]  
(5)

where \( S_{op} \) operational expenses of the system, $/kW/year, \( T \) – equipment lifetime, \( K_r \) – electric energy recovery coefficient.

Initial data taken for the calculations is presented in Table 1.

| Table 1. Technical-economic initial data for the calculation. |
|-------------------------------------------------------------|
| Energy storage system installed capacity, MW | \( N_{ac} \) | 100 |
| Specific cost of installed capacity of HOSG, $/kW | \( C_{HOSG} \) | 90 |
| Specific cost of electrolysis equipment, $/kW | \( C_{el} \) | 1400 |
| Energy storage system capacity, kWh | \( E_{st} \) | 600 |
| Specific cost of H\(_2\) and O\(_2\) storage equipment, $/kWh | \( C_{st} \) | 15 |
| Energy storage operation expenses, $/kW/year | \( S_{op} \) | 12 |
| Energy storage equipment lifetime, years | \( T \) | 25 |
| Electric energy recovery coefficient | | 0.37 |

The calculation gives the following main results:

- TPP with 1000 MW of nominal power, operating at coefficient of 0.8 of installed capacity generates 19200 MWh of electric energy. The specified storage capacity in 600 MWh allows to store 3.12% of the total energy generated;
- total cost of hydrogen energy storage system accounts for 123000 thousands $, 85% of which are electrolysis equipment.

4. Conclusion

The use of hydrogen energy storage systems with HOSG is the way to increase TPP maneuverability and reliability due to the following factors:

- the rate of capacity change and startup period of power production unit from various thermal states is limited mainly by inertia of stationary steam generator and in average is 1...1.5 % of nominal capacity per minute. These limitations are removed at use of HOSG based energy storage system. At 100 MW of assigned power and 7 seconds of startup and reaching the nominal regime period, the rate of power change can be increased up to 1 % per second.
- in case of accident development at TPP or NPP, connected with the decrease of the main steam generator capacity by steam mass flow or temperature decrease, the start of HOSG can provide additional power generation during 2…3 hours for the repairs or for slow power unit shut down in a safe mode.

The integration of HOSGs with the main power producing equipment of TPP and NPP must be carried out with respect to the safety issues induced by the presence of flammable and explosive gases. In this connection the storage of hydrogen and oxygen must be placed on the distance from the main equipment required by safety codes and standards. Special attention at system integration should be paid to the steam feeding and mixing channel connecting the HOSG and the main steam line in order to keep low temperature...
non-uniformity in the cross section of steam turbine inlet to avoid additional thermal stress on the turbine blades.

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