Efficiency of Off-Peak Electricity Conversion at Nuclear Power Plants Using Reversible Fuel Cells

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Abstract. The article provides a comparative analysis of the efficiency of off-peak electricity conversion at nuclear power plants (NPP) using reversible fuel cells (RFC). The RFC can ensure the NPP the baseline electrical load through hydrogen production by electrolysis of water, as well as an increase in its maneuverability due to generation of peak electricity. The calculations have shown that at the current stage of technological advancements, the use of RFCs in terms of achievable efficiency of off-peak electricity conversion has advantages over the hydrogen power complex which utilizes an additional steam turbine to generate peak electricity. The achievable advantage equals 2.84-4.25% and 7.72-11.58% at the RFC efficiency in the mode of peak power generation of 50% and 60%, respectively, which is 5.1-7.66 MW and 13.9-20.85 MW more than the generated peak electricity. It should be noted that an increase in the electrolysis mode efficiency facilitates the RFC advantages – from 24.44 to 36.65% and from 29.32 to 43.98% respectively. The use of the "cold" combustion technology for hydrogen fuel ensures not only high efficiency, but also reliability and safety of the hydrogen power complex operation.

1. Introduction

In line with the strategy of NPPs development in Russia until 2050, it is expected that their share will grow up to 22% [1-2]. In this regard, the issues of increasing their safety and efficiency are of particular relevance. Effectiveness of NPPs utilization is associated with provision of their base load, which can be achieved through accumulation of both the nighttime off-peak power, as well as involvement of NPPs during the daily period to participation in the primary regulation of electric current frequency in the power system [3-4]. For this purpose, pumped storage power plants (PSPP) were commonly used [5]. However, their construction requires specific natural conditions, which cannot be provided in the vicinity of NPPs, and as a result, does not allow for combining a NPP with a PSPP into a single power complex. This leads to the fact that a PSPP in the charging mode consumes electricity at the tariff of the power system, which, taking into account specific investments of about 2000 USD/kW, significantly reduces its competitiveness [1-2].

One of the ways to solve this problem can be production of hydrogen and oxygen on the basis of off-peak NPP electricity by electrolysis of water with a temporary storage and utilization aimed to generate peak electricity due to overheating of the working fluid in the NPP steam turbine cycle [6-8]. At present, the problem of providing NPPs with the baseload due to hydrogen production by water electrolysis presents a significant scientific and practical interest across the world [9]. Specifically, hydrogen produced from nuclear power is of great importance in terms of its role cast for planning the...
economy of the future, where it acts as an alternative to the methane conversion method with a minimal carbon footprint. In this regard, the rate of commissioning electrolysis facilities worldwide is increasing. Additionally, hydrogen production at operating NPPs is included in the development strategy of Rosenergoatom Concern [10]. Therefore, a hydrogen power complex using a unit with installed reversible fuel cells (RFC) based on solid polymer electrolyte (SPE) is considered a novel and promising option.

2. Use of RFC with SPE at NPPs

A bifunctional electrochemical cell is an electrochemical device capable of operating both as a water electrolyzer, producing hydrogen and oxygen, and as a fuel cell, producing electrical energy and heat. Bifunctional electrodes allow for combining two electrochemical processes, and consequently, two units including an electrolyzer and a fuel cell, into one, and thereby reduce the amount of materials used, weight, overall dimensions, and cost [11].

Figure 1a shows a schematic diagram of the operation of bifunctional electrochemical cell with SPE. Figure 1b additionally shows a schematic diagram of the RFC operation in the power generation mode. A solid polymer membrane (thin plastic film) is used as an electrolyte. When impregnated with water, this polymer transmits protons, but does not conduct electrons. The fuel is hydrogen, and the charge carrier is a hydrogen ion (proton). At the anode, the hydrogen molecule is split into a hydrogen ion (proton) and electrons.

The main advantages of electrochemical systems with SPE are high efficiency and environmental friendliness, as well as low inertia, including a sufficiently high level of explosion- and fire safety. The cyclic efficiency of energy conversion in a bifunctional element with SPE is 40.4% [11]. The systems including SPE are compact, can be designed with various geometrical configurations, are insensitive to shock, vibration, and radiation, can be applied in vacuum and weightlessness, are noiseless, and do not contain harmful exhaust gases. Continuous supply of fuel and oxidizer, and continuous removal of reaction products ensures their non-stop operation.

Among the advantages of using a solid electrolyte is corrosion reduction, which ensures a longer durability of RFC and its components. The process can be performed at significant pressure drops between the anode and cathode chambers (up to 0.6 MPa, or more). Although the SPE membrane is thin, it has low gas permeability and reduces the probability of reagent mixing. A reduction in the distance between the electrodes up to the membrane thickness leads to a decrease in the ohmic losses in the electrolyte, which is due to gas bubbles.
The achieved lifetime of RFC is within 5000 hours, which accounts for degradation of materials inside the fuel cell, particularly, under cyclic operation conditions with frequent starts and stops. Thus, under conditions of cyclic operation, the degradation of RFC materials is more intensive in comparison with continuous operation mode [13]. In the future, an increase in the service life of BPE up to 40 thousand hours in the continuous mode is predictable. Figure 2 shows a schematic diagram of combining NPPs and electrochemical hydrogen cycle based on BPE, taking into account peculiar features of thermal regulation [14]:

Alternatively, the known approach to hydrogen thermal storage (HTS) and peak electricity generation at NPPs is considered, which implies direct utilization of hydrogen fuel energy in the cycle of the main or supplementary steam turbine unit (STU) [15].

### 3. Methodology for assessing effectiveness of RFC at NPP

The amount of off-peak night power of the NPP for the production of hydrogen and oxygen, MWh/day:

\[
E_{\text{off-peak}} = N_{\text{off-peak}} \cdot \tau_{\text{off-peak}},
\]

where \( N_{\text{off-peak}} \) is night off-peak power of NPP used to produce hydrogen and oxygen, MW; \( \tau_{\text{off-peak}} \) is duration of the night off-peak period of the NPP electrical load, h/day.

At the same time, the amount of useful energy used for hydrogen and oxygen production, MW:

\[
E_{\text{net}} = N_{\text{off-peak}} \cdot \tau_{\text{off-peak}} \cdot \eta_{\text{RFC}} \cdot (1 - \alpha_{\text{compr}}) \cdot (1 - \alpha_{H_2-O_2}),
\]

where \( \eta_{\text{RFC}} \) is efficiency of RFC in the electrolysis mode; \( \alpha_{\text{compr}} \) is relative power consumption for auxiliary needs when compressing hydrogen and oxygen when supplied to the storage tank; \( \alpha_{H_2-O_2} \) is relative power consumption for auxiliary needs in electrolysis mode when generating hydrogen and oxygen.

Mass of generated hydrogen during the night off-peak period, kg:
\[ G_{H_2} = \frac{E_{\text{net}}}{Q^h}, \]

where \( Q^h \) is the lowest heat of combustion of hydrogen, kWh/kg (33.3 kWh/kg) [16].

The corresponding number of moles of hydrogen:

\[ \text{Mole}H_2 = \frac{G_{H_2} \cdot 1000}{\mu_{H_2}}, \]

where \( \mu_{H_2} \) is the molar mass of hydrogen, g/mol.

Stoichiometric number of moles of oxygen:

\[ \text{Mole}O_2 = \frac{\text{Mole}H_2}{\zeta}, \]

where \( \zeta \) is the molar ratio (stoichiometric) of hydrogen to oxygen, equal to 2.

Stoichiometric mass of produced oxygen, kg:

\[ G_{O_2} = \frac{\text{Mole}O_2 \cdot \mu_{O_2}}{1000}, \]

where \( \mu_{O_2} \) is the molar mass of oxygen, g/mol.

Peak electricity generation in RFC, MWh/day:

\[ E_{\text{peak}} = E_{\text{net}} \cdot \eta_{\text{RFC}} \cdot \eta_{\text{inv}} \cdot \left( 1 - \alpha_{\text{AN}}^{\text{rc}} \right), \]

where \( \eta_{\text{RFC}} \) is the efficiency of RFC in fuel cell mode; \( \eta_{\text{inv}} \) is inverter efficiency; \( \alpha_{\text{AN}}^{\text{rc}} \) is the share of energy for auxiliary needs in the generation of peak electricity.

In this case, the generated peak power due to RFC in the electrochemical hydrogen cycle will be, MW:

\[ N_{\text{peak}} = \frac{E_{\text{peak}}}{\tau_{\text{peak}}}, \]

where \( \tau_{\text{peak}} \) is the number of hours of use of peak power, h.

As a result, the coefficient of effective conversion of off-peak electricity to peak will be, %:

\[ \eta = \frac{E_{\text{peak}}}{E_{\text{off-peak}}} \cdot 100. \]

4. Discussion of the results of the comparative analysis of RFC efficiency at NPPs

For the comparative purposes, we estimated the efficiency of accumulation and use of off-peak electricity at NPPs under combination with RFC compared to an alternative HTA system, which implies utilization of a supplementary STU (see figure 3). In this case, we used the above mentioned methodology, including the methodology of efficiency evaluation of the known approaches to HTA, which are described in detail in [15, 17-19]. For calculation purposes, we used the following basic input data presented in table 1 [1, 15, 20-21]:

\[ \text{Table 1} \]
Table 1. Input data for comparative analysis.

| Parameter                                                                 | RFC  | HTA  |
|---------------------------------------------------------------------------|------|------|
| Duration of off-peak energy use (hours)                                  | 9    |      |
| Consumed night off-peak power from NPP with VVER-1000 (MW)               | 100  |      |
| Duration of peak electricity supply (hours)                              | 5    |      |
| Relative electricity consumption for auxiliary needs of hydrogen and     | 5    |      |
| oxygen storage system (%)                                                |      |      |
| Relative electricity consumption for auxiliary needs in electrolysis      | 5    |      |
| mode in conditions of hydrogen and oxygen generation (%)                 |      |      |
| Efficiency in electrolyzer mode (%)                                      | 60-90|      |
| Efficiency in peak power generation mode (%)                            | 50, 60| 36  |
| Converter efficiency (%)                                                 | 98   |      |
| Relative power consumption for auxiliary needs under peak power          | 5    |      |
| generation (%)                                                           |      |      |

Figure 3 shows the results of comparative analysis of efficiency of off-peak accumulation and peak electricity generation at NPPs with VVER-1000 for the considered options of hydrogen power complex, depending on the efficiency of water electrolysis process:

![Figure 3](image_url)

**Figure 3.** Calculation results of the efficiency of off-peak electricity conversion (a) and peak power generation (b) at NPPs at combination with RFC in comparison with HTA: 1, 2 – RFC with efficiency in the electrolyzer mode at 50% and 60%, respectively; 3 – HTA.

Figure 3 demonstrates that combination of NPP with RFC is more effective compared to the HTA-based system in terms of accumulation efficiency and production of peak electricity. It is associated with higher efficiency of RFC-based system operating in the peak power generation mode. At the same time, the advantage of RFC is 2.84-4.25% and 7.72-11.58% with the efficiency in the mode of peak power generation of 50% and 60%, respectively, which is 5.1-7.66 MW and 13.9-20.85 MW more than the generated peak power. It should be noted that with an increase in the efficiency of the electrolysis mode, the RFC benefits become still more evident – from 24.44 to 36.65% and from 29.32 to 43.98% respectively. Considering that at present RFC-based plants are at the stage of pre-industrial implementation, that will significantly affect the cost of their use, their advantage, in terms of accumulation efficiency and production of peak electricity, makes them attractive for further application due to improvement of production technologies and materials. At the same time, a significant advantage of the "cold" hydrogen fuel combustion technology used for RFCs is obvious, which is an important factor in ensuring reliability and safety of their operation.
5. Conclusion

- A promising approach to providing NPPs with base load and increasing its maneuverability by generating peak power using a hydrogen energy complex based on reversible fuel cells is considered. Due to the use of "cold" hydrogen fuel combustion technology, this approach provides not only high efficiency, but also upgrades reliability and safety of the hydrogen power complex performance.

- A methodology has been proposed and a comparative assessment of the hydrogen energy complex has been performed based on reversible fuel cells and a system based on hydrogen-thermal accumulation in terms of efficiency of off-peak NPP power conversion.

- The calculations have shown that a combination of NPPs with RFCs is more effective, which is explained by higher efficiency in the mode of peak power generation. Moreover, the RFC advantage is 2.84-4.25% and 7.72-11.58% with the efficiency in the mode of peak power generation of 50% and 60%, respectively, which is about 5.1-7.66 MW and 13.9-20.85 MW more than the generated peak electricity. It should be noted that an increase in the efficiency of the electrolysis mode, results in the growing advantages of the RFC system – from 24.44 to 36.65% and from 29.32 to 43.98% respectively.

6. References

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