Participation efficiency of the NPP with the hydrogen production facility in primary frequency regulation of the power system

R Z Aminov, A N Bairamov

Department of Energy Problems of the Saratov Scientific Center of the RAS
Russia, 410054 Saratov, Polytechnic st., 77, office 13
oepran@inbox.ru

Abstract. The aim of the paper is to estimate economic benefits from participation of an NPP with the hydrogen production facility (HF) in the primary frequency regulation in the power grid. We provide the main requirements for the NPP power units utilized in the primary frequency control in the power grids. It is shown that according to the given requirements, operation of an NPP is associated with shortage of electric power caused by unloading and consequent decay in NPP efficiency. Therefore, one of the ways to raise the NPP participation efficiency in the primary frequency control is its integration with the hydrogen production facility which eliminates the need for unloading the NPP power unit. This ensures operation of the steam turbine facility and the nuclear reactor with the nominal power level during 24 hours. Additionally, conditions are provided for the generation and storage of hydrogen and oxygen within 24 hours, which allows using them to overheat the working fluid of the NPP steam turbine cycle for further production of peak power.

1. Introduction
According to the Energy Strategy of Russia for the period until 2035 [1], development of nuclear energy and a closed nuclear fuel cycle is determined as strategic priority. Thus, providing NPPs with the baseload capacity is a challenging issue. To achieve the aim, the researchers in and outside Russia are developing the scientific basis [12–14] for utilization of the hydrogen production systems [2–11] alongside with pumped storage plants. An advantage of the hydrogen facility is a possibility to consume power directly from an NPP at the cost of night off-peak hours for the production of hydrogen and oxygen, whereas a pumped storage plant is charged from the power system at the rate 3–4 times higher than the cost of the NPP energy.

In this case, hydrogen can be used to generate on-peak energy when using steam/hydrogen steam overheating of fresh steam before the main turbine (figure 1a) [2, 6–11, 15–17], or with installation of an additional turbine operating on steam removed from the reheat system (figure 1b) [18–23].

Efficiency of NPPs with the hydrogen facility under variable loads within the daily power consumption was considered in [2]. This paper deals with estimating efficiency of the hydrogen facility utilized in the primary frequency regulation.
2. Requirements for power units when using nuclear power plants for frequency regulation in the power systems

One of requirements to the power systems is the necessity to regulate the frequency and keep it within acceptable limits. For this purpose, specially designated thermal power plants as well as hydroelectric power stations are involved. According to the order of the System Operator of the Unified Power System as of 19 August 2013 № 314 [24–26], the basic requirements for the primary frequency control by NPP power units are formulated.

According to the requirements relating the standard on operational dispatch control in the electric power sector [25], the frequency must range within $50 \pm 0.2$ Hz and not less than 95% of the day part without exceeding the maximum $50 \pm 0.4$ Hz. In this case, the means of secondary frequency control combined with primary frequency regulation facilities must keep the frequency within $50 \pm 0.05$ Hz (normal level) or within $50 \pm 0.2$ Hz (permissible level), and restore the normal frequency level within at least 15 minutes.

Nuclear power plants are commonly used in the basic part of the load schedule, which is facilitated by two important factors:

1. High investment level, lower costs of electricity compared to other thermal power plants due to low share of fuel input costs.

2. Technical challenges related with unloading and subsequent power ascension arising at certain periods of the fuel cycle of an NPP caused by xenon poisoning of the reactor core (iodine pit). Moreover, operation the basic mode stabilizes the rate of an NPP reliability at sufficiently high level, and ensures long life for costly facilities.

It should be noted that involvement of NPPs into the primary current frequency control process of the power systems is associated with the likely frequent changes in the load rate.

To participate in the primary frequency control, the start-stop characteristic of the NPP generating equipment must satisfy the following requirements [24]:

1) under frequency deviations, it should be guaranteed that the generating equipment will participate in the primary frequency control by means of the required primary power rate within the range limit:
   – to load up to 2% of the rated electric capacity of a power unit;
   – to unload up to 8% of the rated electrical capacity of a power unit;
2) in case of frequency jumping, which requires implementation of the primary power within the specified ranges, it shall be ensured:
– realization of no less than half of the required primary capacity within at least 10 seconds;
– realization of the whole required primary capacity within no more than 2 minutes.

Thus, in line with the requirements to dynamics of the primary capacity of the NPP power unit, at the maximum required primary power for loading ΔП =2 % P_{nom} should be no worse than 1 % P_{nom} per 10 sec., 2 % P_{nom} per 30 sec.; at the maximum required primary power for unloading ΔП = -8 % P_{nom} the dynamics of the primary power of the power unit should be no worse than -4 % P_{nom} per 10 sec., -8 % P_{nom} per 120 sec. [24].

Approximate dynamics of the power rate at NPP power units depending on frequency fluctuations is shown in figure 2 for the cases relating the maximum primary power output at 2% P_{nom} (figure 2a), and the maximum primary power for unloading at 8% P_{nom} (figure 2b) [24].

**Figure 2.** Dynamics of power changes in NPP power units: a) simulation of frequency increase in the power system; b) simulation of frequency reduction in the power system.

Thus, according to figure 2a, increasing the frequency by Δf = 240 MHz, is supposed to result in the required reduction of capacity in the power unit by 4 % P_{nom} within the period t ≤ 10 s, and by 8 % P_{nom} within t ≤ 2 min. Elimination of the frequency increase by Δf = 240 MHz , will result in the corresponding increase of capacity in the power unit up to initial value with the required speed (1 % P_{nom} / min) permissible for reactor operation.

In accordance with figure 2b, if the frequency deviates by Δf = -60 mHz, then the changes in the capacity of the power unit should be by 1 % P_{nom} within the time span t ≤ 10 sec., and within t ≤ 30 sec. by 2 % P_{nom}.

These requirements determine the daily operation of the NPP power unit under the inefficient unloading mode in order to maintain the necessary capacity reserves around 2% from the nominal rate. At the same time, when the frequency grows, there is a need for additional unloading up to 8% of the rated capacity. As a result, the NPP faces a shortage of electrical power, including decrease in the absolute internal efficiency of the cycle due to pressure reduction by 0.34% and 1.54%, while operating at the capacity level of 98% and 92% from the nominal value, respectively (figure 3. Example of an NPP with installed PWR-1000).

It should be noted that unloading an NPP results in the annual reduction of nuclear fuel consumption.

In the case of combining the NPP with the hydrogen facility, it becomes possible to maintain the needed reserve of produced power required for loading due its consumption in hydrogen and oxygen production in electrolysis systems, and their accumulation in storage systems. At this, the turbine generator and the reactor remain unloaded and proceed operating at the nominal power level. An increase in the power supplied to the grid by 2% can be ensured by shutting down electrolysis and compressor facilities.
Additional reduction in NPP electricity power supply to 8% of the nominal rate can be ensured by a bigger loading to electrolyzers and compressors without reducing the nominal power level at the power unit. Additionally, an NPP with the hydrogen production facility can participate in providing peak power demand due to hydrogen and oxygen accumulated when providing reserve power by 2%, which ensures additional economic effect.

An important advantage of the NPP with the hydrogen facility is elimination of risk of inefficient modes for reactors, which is associated with xenon poisoning of the core region ("iodine well") under frequent discharges with small reactivity reserves, which can lead to complete shutdown of the power unit for minimum 20 hours. This is particularly important for unloading periods up to 8%. Therein, for the unloading process this problem is solved by a temporary removal of the NPP power unit from the primary control system when the reactivity margin is at the minimum. In this case, participation in the regulation process, instead of the removed power unit, is conducted by the replaceable NPP power unit through increasing its reserve capacity.

3. Requirements for power units when using nuclear power plants for frequency regulation in the power systems

As in the case of the NPP with PWR-1000 reactor, taking into account the combination with the hydrogen production facility, based on the requirements and in accordance with the power dynamics, reduction in the supply of electric power to the grid can reach up to 80 MW, whereupon it is necessary to reduce the output by 40 MW within the first 10 seconds. The overall time, when it is necessary to ensure reduction in the power output to the required capacity level must be no more than 2 minutes.

In the case of power generation for the loading, the power unit should ensure an increase by about 20 MW of the output power to the grid within no more than 30 seconds.

It should be noted that the main facility of the hydrogen system is capable to start the loading process and the unloading in accordance with the rate of power changes in the main turbine generator at the minimum time delay. These transition processes can be regulated by the automation system. The established capacity of electrolyzers may be at 50 MW and provided by two units [2, 6–11].

Thus, the load changes in the hydrogen facility will be in the range of 80 MW. The maximum load level in the hydrogen system will reach at the maximum reductions of power supply to the grids. Meanwhile, in the first 10 seconds, the loading rate of electrolysis devices should be around 3.5 MW/sec., after which prior to expiration of 1 min. 50 sec. the loading rate may be kept lower than 0.5 MW/sec, with account for operation of compressor facilities used to supply hydrogen and oxygen to the storage system with consumed power about 5.6 MW. The given load rate can be provided by changing the current intensity in electrolyzers.

Under these conditions, electrolyzers with the solid-polymer electrolyte are given top priority. This type of electrolyzers, compared to the alkaline, can ensure a wider range of power intensity since there are no challenges with gas filling of electrolytes at the load increase, which reduces efficiency of

![Figure 3. Absolute internal efficiency of the NPP cycle on wet vapour.](image-url)
electrolysis processes [27]. Given that, electrolysis and compressor facilities are maintained in working condition, which reduces time for start-up operations.

4. The method for estimating participation efficiency of NPPs with hydrogen production systems in the primary frequency regulation within power systems (as in the case of the NPP with installed PWR-1000)

The assessment method is based on comparing economic benefits of NPPs operating with unloading and operating with the nominal power rate due to integrated hydrogen production facility. The approximate number of NPP participations in frequency regulation within 24 hours, both at increased power for the loading by 2% of the nominal rate, and with account for reduced power output up to 8% of the nominal rate, is established from 1 to 6.

It should be noted that economic benefits from the energy marketing at the increase of the NPP capacity from 98% to the nominal rate, despite its short-term nature, is taken into account in both versions.

For the cases of NPP operation with the unloading process, economic benefits are estimated as a result of reduction of nuclear fuel consumption, as well as undersupply of energy to the replaceable power unit of the NPP.

In the case of the NPP with the hydrogen facility, economic benefits from production of peak power is estimated taking into account for utilization of steam/hydrogen superheating of the working fluid in the steam-turbine cycle of the NPP based on the scheming in figure 1a.

Economic benefits from peak power marketing at duration of 1 hour / day was determined for power consumption of the NPP power unit at 2% from the nominal rate for the production of hydrogen and oxygen during 24 hours. Whereas the time needed for the production of hydrogen and oxygen was around 23 hours / day with the number of NPP participations in the regulation equal to 1, and around 22 hours / day at 6 participations. Efficiency of transformation into peak power was about 35% [2, 6–11] with potential future efficiency of electrolyzers at the level of 75-80%. The established tariff rate for the peak power and its prime cost for the NPP output ( \( \frac{T_{peak}}{S_{NPP}} \) ) – 2.2, 2.8, 3.3, 3.9. At the same time, the cost of the NPP power at the relative capital investments at the level of $ 2,500 / kW was 0.9 and 1.05 rubles / kWh, with the target prices for nuclear fuel in the years 2020 and 2035, respectively. The peak power produced was about 100 MW.

The overall amount of economic benefits for both options in general terms, rubles / year, can be given as:

\[
R_{NPP_{unload}} = R_{2\%} + R_{load} - L_{unload}^{lostpower},
\]

\[
R_{NPP+HF} = R_{2\%} + R_{peak} - L_{NPP+HF}^{lostpower},
\]

where \( R_{NPP_{unload}} \) is economic effect resulting from participation of the NPP power unit in the primary regulation due to unloading process, rubles / year; \( R_{NPP+HF} \) is economic effect as a result of participation of the NPP power unit combined with the hydrogen facility in the primary regulation, rubles / year; \( R_{2\%} \) is economic effect from marketing energy of 2% from the nominal rate, rubles / year; \( R_{load} \) is economic effect received due to decreasing consumption of nuclear fuel, rubles / year; \( R_{peak} \) is economic effect from marketing peak power due to steam/hydrogen overheating in the steam-turbine cycle of the NPP, rubles / year; \( L_{unload}^{lostpower}, L_{NPP+HF}^{lostpower} \) are economic losses from under-supply of energy in the case of unloading and combining the NPP with the hydrogen production facility respectively, rubles / year.

Economic effect due to increase in power output by 2% of the nominal rate, rubles / year:

\[
R_{2\%} = E_{output_{2\%}} T_{power},
\]

where \( E_{output_{2\%}} \) is electricity supply of 2% from the nominal rate, kW·h / year; \( T_{power} \) is the tariff for electricity supplied from the NPP, rubles / kW·h.

Economic effect resulting from the decrease in nuclear fuel consumption, rubles / year:
\[ R_{\Delta B_{\text{nf}}} = \Delta B_{\text{main}} \tau_{\text{unload}} C_{\text{n.f.}} + \Delta B_{\text{replaceable}} \tau_{\text{unload}} C_{\text{n.f.}}, \]  

where \( \Delta B_{\text{main}} \), \( \Delta B_{\text{replaceable}} \), \( \tau_{\text{unload,main}} \), \( \tau_{\text{unload,replaceable}} \) is reduction in the consumption of nuclear fuel by the main and replaceable NPP power units, kg of fuel equivalent/year; \( \tau_{\text{unload,main}} \), \( \tau_{\text{unload,replaceable}} \) is operation time of the main and replaceable power units of the NPP with unloading, h / year; \( C_{\text{n.f.}} \) is the price of nuclear fuel, rubles / kg of fuel equivalent.

Nuclear fuel cost projections for year 2020 were established at $20 per ton of fuel equivalent ($2.5 / MWh), and for the target period till year 2035 were established at $27 / ton of fuel equivalent ($3.3 / MWh) [28].

Since unloading of NPPs to 8% of the nominal rate is short-term compared to continuous operation of the power unit at unloading of 2% of the nominal rate, reduction in consuming nuclear fuel was prioritized for operation of the power unit at 98% capacity. The annual decrease in consumption of nuclear fuel was about 3.65-3.74 tons of fuel equivalent per year, where the lower value corresponds to the number of participations of the NPP in frequency regulation through application of the loading capacity as equal to 6 per day and, accordingly, bigger fuel saving under single participation per 24 hours.

The cost advantages from peak power marketing, rubles / year:

\[ R_{\text{peak}} = E_{\text{peak}} T_{\text{power}} \]  

where \( E_{\text{peak}} \) is the annual peak power output of NPPs under conditions of steam/hydrogen overheating of the working fluid, kW·h / year; \( T_{\text{power}} \) is the tariff for the NPP power in the peak period, RUR / kW·h.

Economic implications from undersupply of energy in case of unloading, rubles / year:

\[ L_{\text{unload}} = E_{\text{lost}} T_{\text{power}} = E_{\text{lost,main}} T_{\text{power}} + E_{\text{lost,replaceable}} T_{\text{power}}, \]  

where \( E_{\text{lost,main}} \), \( E_{\text{lost,replaceable}} \) is the undersupply of energy by the main and replaceable NPP power units, kW·h / year.

Economic implications from the under-supply of energy in the case of NPPs with the hydrogen production system, rubles / year:

\[ L_{\text{NPP+HF}} = E_{\text{lost}} T_{\text{power}} \]  

The lost energy in the case of direct participation of NPPs in the regulation process, kW·h / year:

\[ E_{\text{lost}} = E_{\text{lost,2%}} + E_{\text{lost,8%}} \]  

where \( E_{\text{lost,2%}} \) is the lost energy due to maintenance of power reserves of the power units at 2% of the nominal rate, kW·h / year; \( E_{\text{lost,8%}} \) is the lost energy as a result of reduction of power supply by 8% of the capacity from the nominal rate, kW·h / year.

The comparison analysis was based on the indicator \( \Delta R = R_{NPP+HF} - R_{NPP\text{load}} \). In this case, taking into account that the values of \( R_{\text{2%}}, R_{\text{8%}} \) are considered equal for both variants, then after the required transformations, \( \Delta R \) will take the form, rub./year:

\[ \Delta R = R_{\text{peak}} - R_{\Delta B_{\text{nf}}}. \]  

Figure 4 shows the results of calculations of \( \Delta R \), taking into account the nuclear fuel cost projections for the year 2020 (figure 4a) and 2035 (figure 4b), depending on the tariff rates for peak power and the NPP energy costs.

As is seen in provided assessment, NPP participation in frequency regulation in case of combining with the hydrogen production facility is considered more effective. Therein, an important role is played by producing peak power due to steam/hydrogen overheating of the working fluid, which significantly upgrades economic benefits from reducing consumption of nuclear fuel, which consequently leads to improvement of the target results.
Figure 4. Participation efficiency of NPP power units with PWR-1000 in the primary frequency regulation within the power system: a) under nuclear fuel cost projections for year 2020; b) the same for year 2035; 1) the number of NPP participations in regulating frequency due to unloading (reduced output of energy) by 2% and 8% of the nominal rate equal to 1 per day; 2) the same due to unloading (reduced energy output) by 2% and 8% of the nominal rate equal to 6 per day.

5. Conclusion
Using NPP power units in primary frequency regulation is associated with frequent load changes in the turbine generators. Maintaining the required capacity reserves leads to economic implications caused by undersupply of energy as a result of unloading of the plant. Thus, NPP power units with hydrogen production facilities allow for providing the needed power reserves, as well as participation in the primary frequency regulation due to generation and storage of hydrogen and oxygen without reducing the nominal power rate of the turbine generator and the reactor during the period of 24 hours.

As the estimates show, the rate of economic benefits from application of the hydrogen production system with account for peak power at the level of 100 MW due to utilization of steam/hydrogen overheating of the working fluid of the NPP steam-turbine cycle, results in economic benefits compared to the cases with unloading processes.
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