How to Deal with the Threat of New Energy to the Safe Operation of Nuclear Fuel

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Abstract. In the last decade, with the carbon peaking and carbon neutrality goals, wind generation and solar photovoltaic generation have been increasing their share of the power grid. Now, it has become normal for nuclear power plants to participate in peak load regulation of the grid. During peak load regulation at the nuclear power plant, the change of reactor power brings the temperature change of fuel cladding and pellet. The pellet-cladding interaction caused by the temperature change of fuel pellets maybe cause the damage of fuel rod cladding, which will greatly threaten the safety of nuclear fuel. In this paper, firstly, the depth of peak load regulation in the nuclear power plant is discussed. Secondly, the power increase/reduction speed in the process of peak load regulation is researched to reduce the thermal stress effect of pellets. In addition, the risk of the local power of the reactor is discussed. At last, some other peak load regulation solutions for nuclear power plants, such as nuclear energy for heat supply, steam supply, pumped storage power plant, and battery storage are being explored.

Keywords: Peak load regulation · Nuclear fuel safety · Fuel cladding · Fuel pellet · Control mode · AO · DNBR · Temperature gradient

1 Energy Situation

Driven by the global energy transition, China, as the largest energy consumer, has been pushing forward its energy revolution in the past decade, and has proposed the strategy of "carbon peaking and carbon neutrality", i.e., "we aim to peak carbon dioxide emissions by 2030 and achieve the goal and vision of carbon neutrality before 2060". Under the guidance of the "carbon peaking and carbon neutrality" strategy, China's energy structure has been continuously optimized, taking data of 2021 as an example: coal consumption accounts for 56.0% of total primary energy consumption, oil for 18.5%, natural gas for 8.9%, and clean energy for 25.5%. Compared to 2012, the proportion of coal consumption in China has decreased by 12.5% points and that of clean energy consumption has increased by 11% points (Fig. 1).

According to the data, by the end of 2022, China's installed capacity of nuclear power has reached 56.89 million kW, nearly 4.5 times of that in 2012. In the past decade, China's nuclear power has stepped into a new stage of safe and efficient development (Fig. 2).

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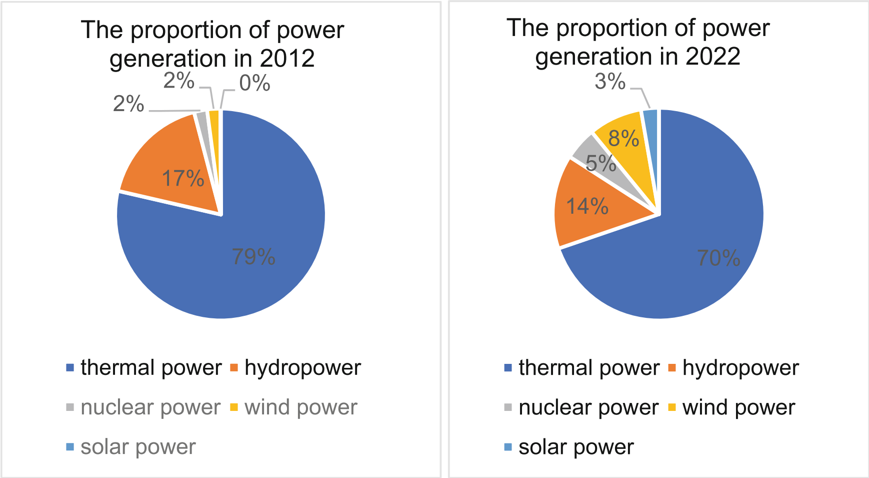

Fig. 1. The proportion of power generation in 2012 & 2022

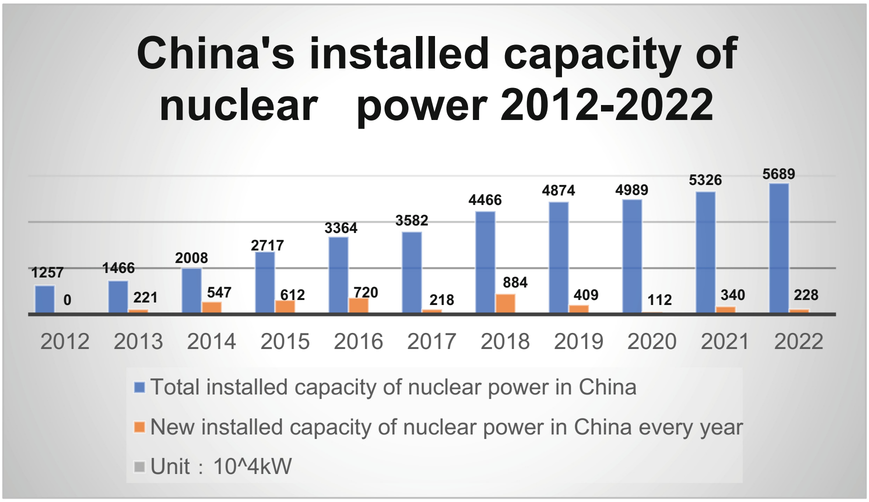

Fig. 2. China's installed capacity of nuclear power in 2012–2022

In terms of renewable energy development, China's newly installed wind and photovoltaic power generation capacity has reached 125 million kW in 2022, exceeding 100 million kW for three consecutive years and created a new record. Wind and photovoltaic power generation capacity has reached 1.19 trillion kWh, an increase of 207.3 billion kWh compared to 2021 with a growth of 21% on year-on-year basis, accounting for 13.8% of the total electricity consumption in China, with an increase of 2% points year-on-year (Fig. 3).

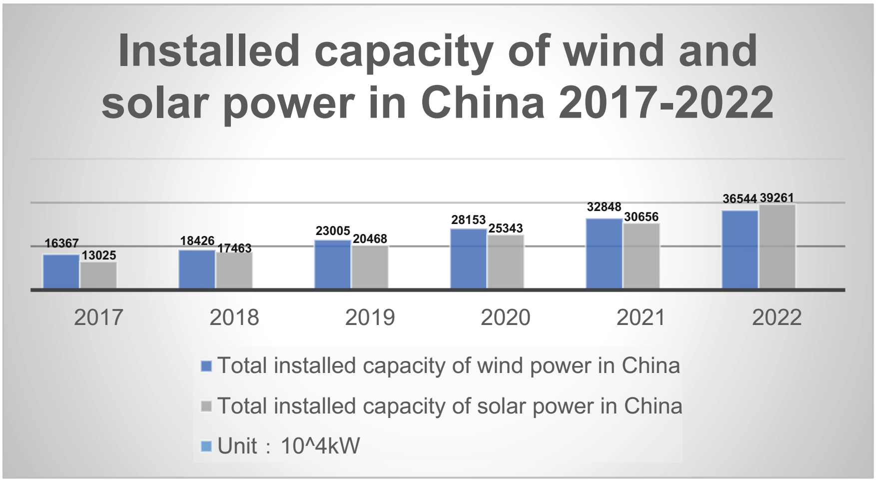

Fig. 3. Installed capacity of wind and solar power generation in China in 2017–2022

2 Analysis of the Situation of Nuclear Power Units Peak Load Regulation

In recent years, with the help of domestic conditions and government policy support, China has taken the lead in the development of wind power, photovoltaic and other renewable energy in the world, and its proportion of installed capacity has surpassed that of nuclear power units. In addition, the intermittent and random features of wind power and photovoltaic power sources dictates that they not only can't provide the peak load regulation ability that the power source should have, but also show the characteristics of reverse peak load regulation during certain periods.

In provinces with large installed nuclear power units and regions with rapid growth of nuclear power installed capacities, the power grid is in conformity with the characteristics of weekends and festivals. Maintaining full power operation of nuclear power units will increase the difficulties in peak load regulation. During low load periods, the problem of insufficient reserve is prominent, and there are risks of water and wind abandonment, which is inconsistent with the concept of efficient utilization of renewable energy. Therefore, for the moment, power grids in provinces such as Zhejiang, Fujian, and Liaoning, etc. need to decrease load to participate in peak load regulation during the Spring Festival, National Day and other special load days [1].

The following Fig. 4 shows the annual average peak load regulation times of a power station in China from 2020 to 2022. It can be seen that the annual number of peak load regulation times of each unit varies according to the situation, but the number of total peak load regulation times of the power station still shows an increasing trend year by year.

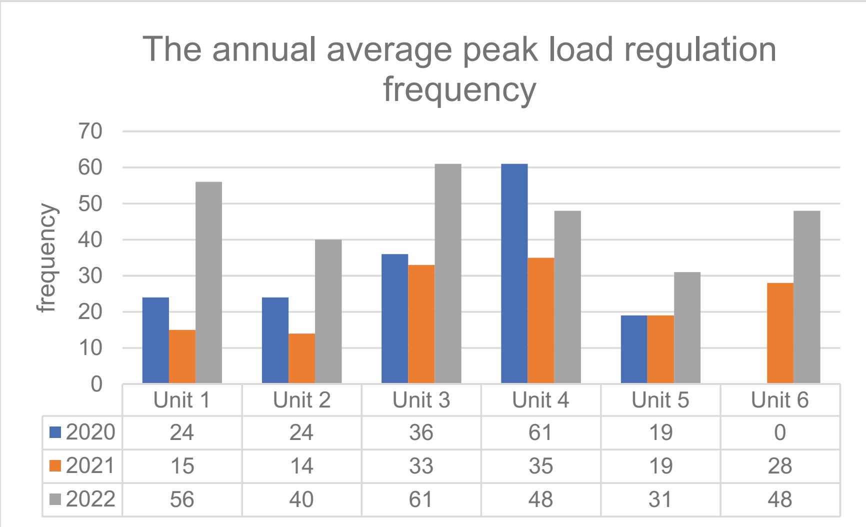

Fig. 4. The annual average peak load regulation frequency

3 Technical Measures to Deal with Nuclear Power Units Peak Load Regulation

The nuclear fuel assembly contains hundreds of fuel rods. Generally the clad is made of zirconium alloy and filled with UO_2 fuel pellets. The zirconium alloy cladding tube and the end plugs at both ends serve to contain the fuel pellets, allowing the radioactive fission products produced by the fission of the fuel pellets to be contained within the fuel cladding.

Frequent participation of nuclear fuel in peak load regulation may increase PCI effect. PCI effect refers to the interaction between fuel pellets and cladding in a reactor. Frequent peak load regulation leads to drastic temperature changes in fuel assembly, and fuel pellets form hourglass structure due to uneven thermal expansion. The fuel cladding generates ring ridges on the shoulder of corresponding pellets, and leads to local stress concentration near the ring ridges, which may lead to local fatigue damage of fuel cladding (Fig. 5).

According to research reports such as EPRI's *Fuel Reliability Guidelines: Pellet-Cladding Interaction, IAEA Nuclear Energy Series–Review of Fuel Failures in Water Cooled Reactors* and relevant practical experience, frequent participation of nuclear power units in peak load regulation, mediation and deep peak load regulation will increase the probability of nuclear fuel failure. Therefore, it is necessary to take corresponding technical measures to control the peak load regulation.

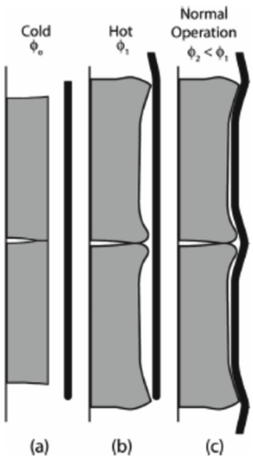

Fig. 5. Diagram of PCI effect

3.1 Balance of the Amplitude and Frequency of Peak Load Regulation with Multi-reactor Management

It can be seen from the above table on peak load regulation data of 6 units that the method of power reduction sharing can maximize the use of multi-reactor management concept, take advantage of units with large capacity in nuclear power base, reduce the range of reactor power variation and the probability of PCI effect occurring.

The core of the VVER reactor is composed of 163 groups of fuel assemblies with a refueling cycle of 18 months. Each refueling cycle adopts 1/3 refueling mode, and there are fuels of the first, the second and the third cycles in the core. According to the technical specifications of fuel assemblies and analysis report *The Ability of Units 1–6 of a Nuclear Power Plant to Participate in Power Grid peak load regulation*, the number of Units 1–6 participating in peak load regulation shall be controlled within the scope of less than 150 times, and the warning value is set to be 120 times.

The table below shows the number of accumulative power increasing times of in-core fuel assemblies of Units 1–4 by a certain day (Table 1).

Operation with frequent peak load regulation will increase the PCI effect of fuel elements, increase the risk of fuel assembly damage, and affect the security of nuclear fuel. Therefore, the unit shall be reasonably planned for peak load regulation according to the accumulated number of peak load regulation of in-core fuel assemblies, and operation with peak load regulation shall not be carried out in the reactor that has reached the specified limit.

3.2 Control the Rate of Change of Reactor Power

According to the reactor technical specifications, there are clear requirements for the speed of reactor raising and lowering power, in order to reduce the impact of PCI effect and prevent the loss of fuel assembly airtightness. When the power of the reactor is raised and lowered frequently, according to years' operating experience of the station,

Table 1. Number of accumulative power increasing times of in-core fuel assemblies

Unit	Number of accumulative power increasing times of in-core fuel assemblies
Unit 1	Fuels of the 3rd fuel cycle: 97 Fuels of the 2nd fuel cycle: 74 Fuels of the 1st fuel cycle: 58
Unit 2	Fuels of the 3rd fuel cycle: 65 Fuels of the 2nd fuel cycle: 44 Fuels of the 1st fuel cycle: 3
Unit 3	Fuels of the 3rd fuel cycle: 108 Fuels of the 2nd fuel cycle: 96 Fuels of the 1st fuel cycle: 80
Unit 4	Fuels of the 3rd fuel cycle: 93 Fuels of the 2nd fuel cycle: 71 Fuels of the 1st fuel cycle: 28

the PCI effect will increase sharply, and the possibility of the fuel assembly losing the airtightness will also increase greatly. Therefore, the reactor peak load regulation speed shall be strictly controlled, when the power grid needs peak load regulation of the unit. According to the fuel performance safety demonstration report, technical specifications and operation experience, the suggestions are as follows.

When the accumulative power rise times of the fuel assembly with the longest running time in the reactor are below 60, the controlled power rise speed shall not exceed 10% NP/h; When the number of times is 60–120, the controlled power rise speed shall not exceed 5% Nnom/h; When the number of times exceeds 120, the controlled power rise speed shall not exceed 3% NP/h.

At present, the duration of reactor low-power operation during peak load regulation is short (less than 48 h). Indeed, it is well known that extended reduced power operation (ERPO) enables the cladding to creep down on the pellet stack. Therefore, when the fuel rod goes back to Nominal Power, the thermal expansion of the fuel pellets generates strong hoop stresses in the cladding which in turn could generate a risk of PCI-SCC failure. So, there are corresponding technical requirements in the technical specification, i.e., when the reactor is in continuous operation below Nominal Power for more than 12 days, the power increase rate is required to be no more than 1% NP/h.

3.3 The Moving Speed of the Control Rod

According to the nuclear physical characteristics of the core, when the control rod is withdrew or inserted down, the neutron flux density distribution at the location of the control rod will change significantly, which leads to the increase of neutron flux density gradient of the nearby fuel rod and the great change of fuel rod power (Fig. 6).

In order to prevent the neutron flux density gradient from leading to a large power gradient and causing the exacerbation of PCI effect, it is necessary to strictly control the change of the neutron flux density distribution in the core and the moving speed of

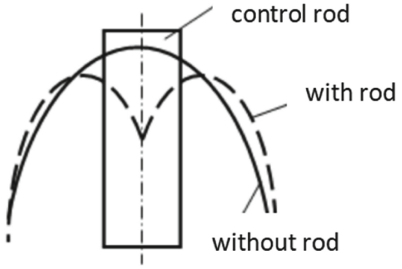

Fig. 6. Neutron flux density distribution during control rod insertion

control rod, so that AO can be controlled within the required range. Therefore, during the unit operation with peak load regulation, Technical Support Branch needs to prepare the reactivity control scheme according to the peak load regulation range, and the operator must strictly implement the reactivity control scheme to ensure that AO, line power density margin and DNBR margin are within the required controllable range.

Taking the peak load regulation data of the third fuel cycle of a power plant unit as an example, there are 93 times of peak load regulations in the third fuel cycle, and the peak load regulation durations are as follows (Fig. 7).

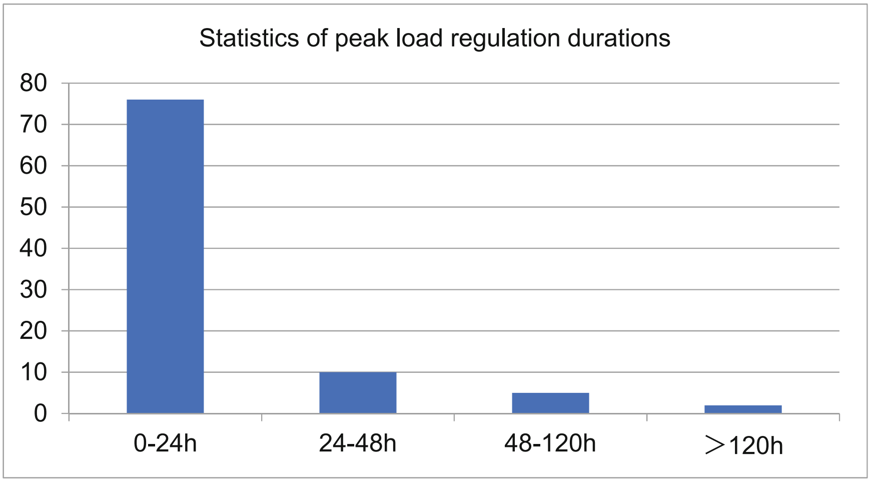

Fig. 7. Statistics of peak load regulation durations

The duration of peak load regulation is different, there are 76 times less than 24 h,10 times between 24 and 48 h, 5 times between 48 and 120 h, 3 times more than 120 h (Fig. 8).

It can be seen from the change trend of primary circuit radioactivity that the material stability of nuclear fuel is well guaranteed by the control methods above in the case of frequent peak load regulation of the unit.

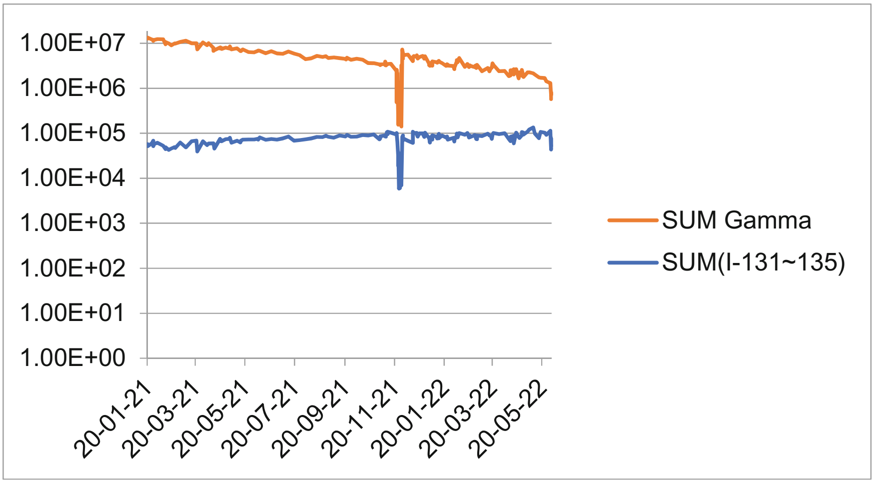

Fig. 8. The trend chart of summary iodine radioactivity and summary Gamma radioactivity in primary circuit of a power plant unit. (Nov.23–29, 2021 was for the unit minor maintenance)

3.4 Conclusion

In face of the current situations of increasing proportion of new energy resources in the power grid and nuclear power units requiring peak load regulation, the safety of nuclear fuel needs to attract more attention.

Therefore, during the development of the peak load regulation strategy for the NPP, deployment and management shall be carried out from the following aspects to control the PCI effect of fuel elements within an acceptable range, and prevent the loss of fuel assembly airtightness or even the damage of fuel assemblies:

(a) The peak load regulation range and frequency of each unit shall be considered comprehensively with multi-reactor management;
(b) To control the speed of reactor raising or lowering power;
(c) To control the range of core parameters during reactor raising or lowering power.

4 Solutions in the Future

Reducing peak load regulation and stabilizing reactor power are important measures to reduce the fuel risk, which can be tried by multiple directions of energy conversion.

4.1 Steam Energy Supply

A steam energy supply project of a nuclear power plant utilizes the main steam in the secondary circuit of the nuclear power unit to produce industrial steam through steam conversion equipment, which is transported to the consumer enterprise in the petrochemical base through the long-distance heat transmission network outside the plant. The design scale of the project is 600 t/h, accounting for approximately 10% of the steam capacity of a unit.

4.2 Pumped Storage Power Station

A certain number of pumped storage power stations can be built in the power grid to meet the needs of peak load regulation, so as to reduce the frequency and range of peak load regulation. As a mountainous area, northern Jiangsu Province can be planned as a suitable place to build reservoirs, which is more suitable for the construction of pumped storage power station.

4.3 Self-built Energy Storage

Utilization of the large-capacity battery packs combining with a variety of new energy generation methods. At present, it is in the experimental stage and far from commercial application stage. Large-scale application is in face of technical bottleneck and cost bottleneck. In recent years, with the breakthrough of sodion energy storage battery technology, the cost of battery will be greatly reduced, and it is expected to be used for power station energy storage in a large scale in the future.

4.4 Grid Construction

The northern Jiangsu region, as an energy base, is relatively backward in economy and the ability to consume electric energy locally is insufficient. Most of the power demands of East China power grid are in northern Zhejiang Province, Shanghai City and southern Jiangsu Province. Therefore, optimizing the construction of power grid and improving the transmission capacity can effectively reduce the peak load regulation condition caused by line power flow limitation.

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