Analysis on capability of load following for nuclear power plants abroad and its enlightenment

Kuan Zheng[1, 4], Fu-qiang Zhang[1], Ting-ting Deng[2], Jin-fang Zhang[1], Weihua Hao[3]

[1] State Grid Energy Research Institute, Beijing, 102209, China
[2] Beijing Jiaotong University, Beijing, 100044, China
[3] State Grid Shandong Electric Power Corporation Maintenance Company, Jinan, 250118, China

E-mail: Kzheng302@126.com

Abstract. With the acceleration adjustment of China's energy structure, the development of nuclear power plants in China has been going back to the fast track. While as the trend of slowing electric power demand is now unmistakable, it enforces the power system to face much greater pressure in some coastal zones where the nuclear power plants are of a comparative big proportion, such as Fujian province and Liaoning province. In this paper, the capability of load following of nuclear power plants of some developed countries with high proportion of nuclear power generation such as France, US and Japan are analysed, also from the aspects including the safety, the economy and their practical operation experience is studied. The feasibility of nuclear power plants to participate in the peak regulation of system is also studied and summarized. The results of this paper could be of good reference value for the China's nuclear power plants to participate in system load following, and also of great significance for the development of the nuclear power plants in China.

1. Introduction

With the acceleration adjustment of China's energy structure, the construction of Nuclear power plants (NPPs) in China has been restarted and went back to the fast track of development. By the end of June 2016, there are 30 nuclear power units being in commercial operation in China with a total installed capacity of 28.6GW, and from January to June in 2016, the cumulative output of the NPPs in commercial operation is 95400GWh, which rose 26.58% compared with those of the same period in 2015 [1]. During the period of the 13th Five Year Plan, we expect that there would be 37.5GW nuclear power to be constructed step by step, and the total installed capacity of nuclear power will reach 58GW by the year of 2020 [2].

There are a few advantages and disadvantages for the rapid development of NPPs. On one hand, it contributes more to a clean energy and reduces the environment stress, and some relevant industries are also driven to develop at the same time. On the other hand, as the proportion of renewable energy power is increasing, the prompt development of NPPs will bring more pressure of the peak regulation for the power system. For this problem, some European and American countries with high proportion of NPPs have owned advanced technology and accumulated rich experience in actual operation, which could provide much reference value for NPPs to participate in the load following and the optimal operation of the power system of China in the future.

2. Regulation capability of NPPs abroad

In 1980s, as a result of improvement of the light water reactor, the output of NPPs can be manoeuvred, and then the system regulators of European and American put forward more and more specific requirements about the adjust and control capability of NPPs. In 1991, the utilities from Great Britain, France, Germany and other countries considered that a more stringent specification would be needed to cover a wide range of designs, and thus the European Utilities Requirements (EUR) were created. The EUR explicitly state that modern reactors should implement significant manoeuvrability capability and, in particular, to be able to operate in the load-following mode [3]:

1) The unit must be capable of continuous operation between 50 and 100% of its rated power (Pr).

The standard plant design shall allow the implementation of scheduled and unscheduled load following operation during 90% of the whole fuel cycle. The unit shall be capable of load-following operation in the range of output from 100% Pr down to the minimum load of the unit. The rate of change of electric output shall be 3% of Pr/min. The unit shall be expected to go through the following number of load scheduled variations, each variation being defined as a transient from full power to minimum load and back to full power:

 2 times per day;
 5 times per week;
 Cumulatively 200 times per year.

2) The unit may be required to participate in emergency load variations:
 Increasing of output: according to requirements for secondary control.
 Decreasing of output:
 Amplitude: down to minimum load of the unit;
 Rate of change: 20% of Pr/min.
3) The unit shall be capable of taking part in the primary control of the grid. This is a prerequisite for connection to the grid. The primary control range shall be ± 2% of the rated power Pr, but higher values may be agreed between system operators and plant operators, though not higher than ± 5% Pr. The unit shall be capable of activating, within 30s, the total primary range of control requested at a quasi-steady frequency deviation of ± 200 mHz, and maintaining supply for at least 15 minutes.
4) The standard plant design shall allow the implementation of a secondary control. The minimum control range for secondary control operation shall be ± 10% of Pr above the minimum load taking into account the control range. The variation rate shall be 1% of Pr/min. Higher values may be agreed between system operator and plant operator, though not higher than 5% of Pr/min.
5) The unit shall be able to contribute to grid restoration. Re-supplying customers will be based on an agreement between the system operator and the plant operator. If the unit participates in re-supplying customers, it should be capable of withstanding sudden load steps up to 10% of Pr.

After decades of development, the modern light-water reactors have already been able to meet all the requirements above. Taking the European EPR and Russian VVER-1000/1200 as examples, the specific parameters of their load following capacity are shown in Table 1.

3. Safety analysis of load following

At present, there is no any disastrous accident of NPP in history, such as the core explosion and the fuel leakage, which are caused by load following. In the development process of more than 60 years of NPPs around the world, there are 3 major nuclear accidents: the accident of Three Mile Island NPP in United States on August 24, 1979, which is ranked level five accident according to the INES scale caused mainly by operation-judgment failure and mechanical failure; the Chernobyl accident in Soviet Union on April 26, 1986, which is ranked level seven accident (the worst accident so far) that happened mainly because of the wrong operation and its design defects; the accident of Fukushima Daiichi NPP in Japan on March 11, 2011, which is ranked level seven accident due to the insufficient design for the tsunami and its aged components and . In conclusion, the key factors leading to those three accidents are design weakness, human errors and scarce capacity for resistance to extreme natural disasters, and it is no relation to the operation mode of NPPs' load following.

Table 1. European nuclear regulatory capacity datasheets

Operating mode	**Typical unit parameters**			
	EPR		**VVER-1000/1200**	
	Adjustment range	Adjustment rate	Adjustment range	Adjustment rate
Daily load following	60%-100%Pr	5%Pr/min	50%-100%Pr	5%Pr/min
	25%-60%Pr	2.5%Pr/min		
Primary frequency modulation	±2.5%Pr	1%Pr/sec	±2%-±5%Pr	1%Pr/sec
Secondary frequency modulation	When the unit output is between min to 60%Pr: ±4.5%Pr	1%Pr/min	±10%Pr	1%-5%Pr/min
	When the unit output is between 60%-100%Pr: ±10%Pr	2%Pr/min		
Emergency situations	Minimum output-100%Pr	Subject to adjustment	50%-100%Pr	20%Pr/min

According to the research report [3], the risk of NPPs load following include two aspects: extended low power operation (ELPO), the other is frequent load following (FLF). However, the accidents caused by these two aspects could not exceed the nuclear power accident with two-level in general. It could cause temperature rise of moderator if low power operation lasts for a long time, and then the risks of fuel the pellet melting and the radioactive fuel leaking to the primary circuit could increase a lot. Moreover, the frequent load following could lead to greater pressure for storage management of radioactive waste and radioactive waste liquid, as well as the radioactive transportation in the future.

4. Economic analysis of load following

The levelized cost of generating electricity (LCOE) is one of the important indicators to measure the power economy. LCOE is closely related to the cost of power supply, operation and maintenance, fuel, emissions, retire and annual power generation. For nuclear power, as the investment cost is its mainly cost and the fuel cost is usually not more than 20% of the total cost, when NPPs participate in the power system load following, the LCOE changes much more than the other power, which is caused by the drop of load rate (the proportion of annual energy output decrease, etc.). According to the data of international atomic energy agency [4] in 2010, on condition that the discount rate is 5%, the load rate decreases from 90% to 70% and the LCOE of nuclear power increases by 35% approximately, which exceeds the coal power with 10% and gas-fired-electric power with 7%.

Since most of modern NPPs implement strong maneuverability capabilities in their designs, there is no or very small impact of the load following on the acceleration of aging of large equipment [5, 6]. However, there is some influence of the load-following on the aging of some operational components (e.g. valves), and thus one can expect a slight increase of the maintenance costs. Also, for older plants some additional investment could be needed in order to become eligible for operation in the load-following mode.

5. The practical operation experience of load following abroad

France is the largest country on the proportion of nuclear power in the world, 75% of its electricity from nuclear power. Because the share of nuclear power in the national energy mix is high, some

NPPs operate in the load-following mode to respond to the daily variations of the electricity demand (see an example in Figure 1) [7]. However, not all the nuclear power units should participate in the frequent load following during the lifetime. In general, the Électricité De France (EDF) will determine the operation mode and maintenance management of nuclear power units together with the power system dispatching department three years ahead of schedule. Among the 58 nuclear power units within the scope of the jurisdiction of the French EDF, there are 10 nuclear power units which do not participate in the power load following, and the amount of participating in the power load following for each nuclear power unit also ranges a lot. For example, according to the data of 2010, the amount of power output of the nuclear power unit whose load following times is the largest reached about 130 times.

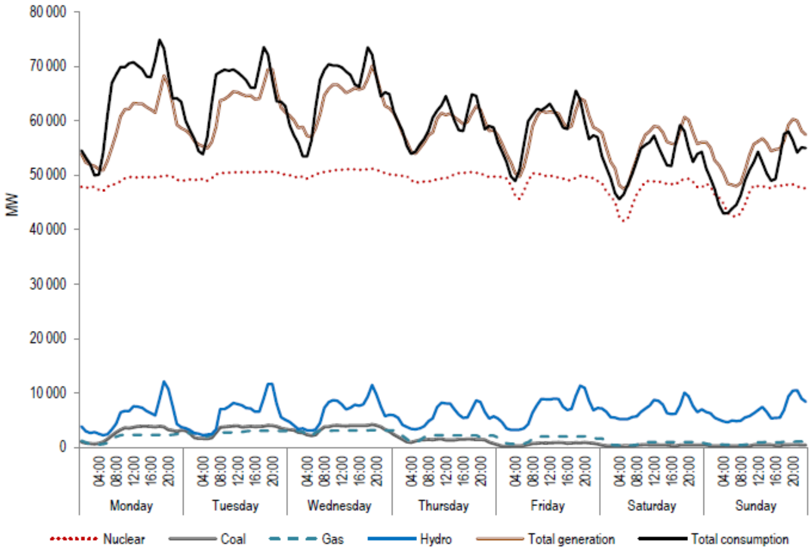

Figure 1. Practical electricity generation in France during 2 weeks in November, 2010.

Although the United States and Japan have the record of nuclear power unit daily load following [8], but since there is enough electricity power with peak regulation capability in these two countries, such as gas-fired power and oil-fired power etc. Therefore, the NPPs of these two countries are operating in the base-load mode in most time. There are some records to show that the PWR nuclear power units of Westinghouse in United States have the practical experience of daily load following operation, and one of the nuclear power units has finished more than 600 times of daily load following operation during the consecutive 4 life times of fuel. Also, the Ikata Nuclear Power Plant of the Shikoku Electric Power Company in Japan has more than 20 years of power load following operation, and the unit No.2 conducted load following in the mode of "12-3-6-3" from October 1987 to February 1988.

Table 2. Practical examples of load following of NPPs in some countries

Country	Reactor type	Control range of load following	Variation rate of output in 1 minute
United States	PWR	50% -100%Pr	About 0.25%-1%
	BWR		
France	PWR	40% -100%Pr	Maximum 5%, Generally 3%
Germany	PWR	50% -100%Pr	5%-10%

6. Conclusion

Compared to the countries with high proportion of NPPs, such as French, the total installed capacity of NPPs in China is small but the development is very fast. During the period of the 13th Five Year Plan, the installed capacity of NPPs in some provinces such as Fujian will increase more than 10% of the total capacity. Analysing the load following capability and the practical operation experience of NPPs abroad indicates that the NPPs can participate in the peak regulation of system by the load following. Although from the economics and safety analysis NPPs is not the best power source to handle the peak regulation of system, the load following operation of NPPs is also of great importance for some provinces in China which are facing big pressure of the peak regulation of system thanks to the fast development of NPPs.

In practice, AP1000, CAP1400 and Hualong No.1 belong to the third-generation reactors of NPPs, which means that the reactors invented by China have the similar load following capability as the French EPR and Russian VVER. However, for China, the performance testing for NPPs, the operation procedures of daily load following and operator training, etc. are lacking. Therefore, for the nuclear power companies and the research institutes should not only learn the technology of load-following of NPPs in France or other countries, but also set the relevant operation specifications and managements for the NPPs operation to change the old opinion that NPPs only operates with base load, what's more, the skills training of the operation personnel for the load following of NPPs is also indispensable to realize the load following of NPPs.

References

[1] The operation statistic of nuclear power from January to June in 2016 in China.China Nuclear Energy Association. http://www.china-nea.cn/html/2016-07/36412.html.
[2] Development plan of nuclear power in China in a long term *National Development and Reform Commission*
[3] Technical and economic aspects of load following with nuclear power plants *Nuclear Energy Agency* http://www.oecd-nea.org/
[4] Operating expearience with nulcear power stations in member states in 2009, IAEA, Vienna, Austria.
[5] Jonas Persson et al. December 2012 Additional costs for load-following nuclear power plants, experiences from Swedish, Finnish, German and French Nuclear power plants ELFORSK rapport **12** 71
[6] Bruynooghe G, et al. 2010 Load-following operating mode at nuclear power plants (NPPs) and incidence on operation and maintenance (O&M) costs. Capability with wind power variability, *JRC Scientific and Technical Reports* SPNR/POS/10 03 004, rev.05
[7] Electrical Energy Statistics for France 2010 RTE. http://clients.rte-france.com/lang/fr/visiteurs/vie/telecharge.jsp.
[8] Yu Wenqi, et al. 2011 A review on load following of pressurized water reactor of nuclear power plants *Energy of China* **33(3)** 38-40.