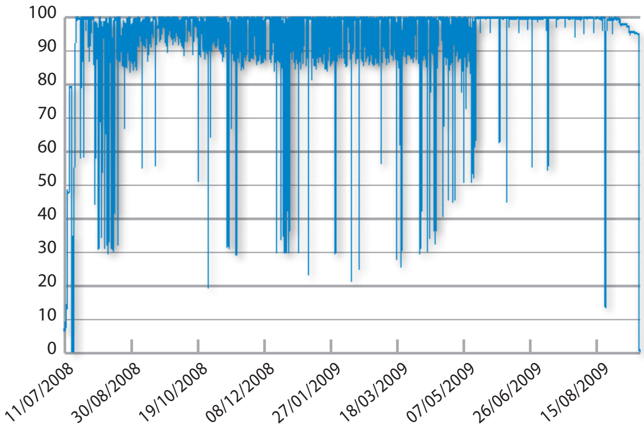
Load-following with nuclear power plants

by A. Lokhov*

Traditionally, nuclear power plants (NPPs) have been considered as baseload sources of electricity as they rely on a technology with high fixed costs and low variable costs. In the beginning of the nuclear era, the share of nuclear power in the overall energy mix was usually small, and adjustments of electric load in response to variations in electricity demand could be left to technologies with different economic and technological characteristics, most notably low fixed cost and high variable cost gas plants. However, this simple state of affairs no longer applies in all countries. The share of nuclear power in the national electricity mix of some countries has become so large that the utilities have had to implement or to improve the manoeuvrability capabilities of their NPPs in order to be able to adapt electricity supply to daily, seasonal or other variations in power demand. This is the case in France where more than 75% of electricity is generated by NPPs, and where some nuclear reactors operate in load-following mode (see Figure 1).

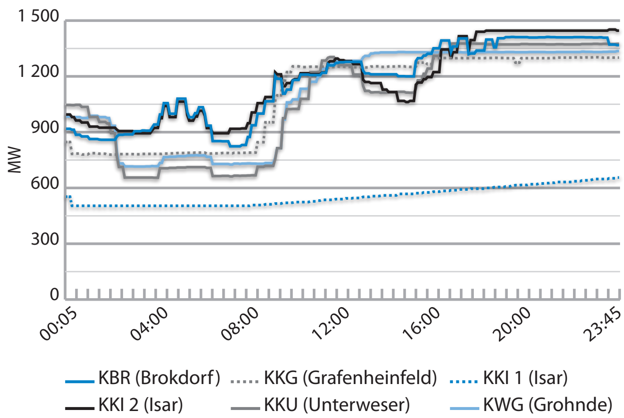
Figure 1: Typical power history during an EDF reactor cycle (in % of rated power)



Courtesy of Électricité de France (EDF).

Another incentive for load-following with nuclear power plants has recently arisen from the large-scale deployment of intermittent electricity sources like wind power. The growing deployment of intermittent sources in several NEA member countries has introduced significant and irregular variations in the power supply and has made balancing electricity supply and demand increasingly difficult. The challenge is not only technical. Due to the sudden influx of large amounts of wind power, German power markets have experienced several hours of *negative* electricity prices in recent years and many more hours with prices that were lower than the variable costs of nuclear power plants, which have the lowest variable costs among the large-scale established power sources. For these reasons, some German utilities have started operating their NPPs in load-following mode (see Figure 2).

Figure 2: Example of load-following during 24 hours at some German nuclear power plants



Courtesy of E.ON Kernkraft.

Grid requirements and manoeuvring with existing nuclear power plants

It is often believed that nuclear power plants cannot operate in manoeuvring regimes. In fact, most of the currently operating NPPs were *designed* to have strong manoeuvring capabilities (NEA, 2011). However, operating an NPP at a constant power level is simpler and less demanding on the plant's equipment and fuel.

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From the technical viewpoint, one of the key design features for the load-following capabilities of the plant is the core monitoring system. Having rapid and precise power distribution measurements provide significant margin for manoeuvring, since the difference between the maximal local power density in the core and its safety limit can be accurately evaluated.

Usually three types of manoeuvring are defined: primary and secondary frequency regulation (which depend on current grid demand) and predefined variable load programmes (i.e. reductions or increases in power output agreed in advance with the grid operator).

Planned reductions or increases in power output allow initial balancing of electricity supply and demand. These variations can be significant. Some units in France have been designed to and indeed do modify on a daily basis their electric output by several tens of per cent of rated power (P_r). Another example is the German Konvoi reactors that were designed for 15 000 cycles with daily power variations from 100% P_r to 60% P_r, and 100 000 cycles with power variations from 100% P_r to 80% P_r (see Ludwig, H., *et al.*, 2010).

Demand for electricity can never be determined with exact precision in advance and thus there is a certain random variation in demand which results in frequency fluctuations of usually less than 20 mHz. The power plants have to monitor the frequency on the grid and immediately adapt their production in order to keep the frequency stable at the desired value. This is called *primary frequency control*. In French nuclear power plants, the corresponding power modulations are performed within ±2% P_r.

The primary frequency control allows short-term adjustments of electricity production according to demand every 2 to 30 seconds. Another type of frequency regulation – *secondary control* – acts over longer time frames (from several seconds to several minutes) and restores the exact frequency by calculating an average frequency deviation over a period of time. For this purpose, the grid operator sends a digital signal to the NPP to modify its power level within a range between ±5% P_r.

Nuclear power plants in France and Germany operate in load-following mode, thus participating in the primary and secondary frequency control of the grid, and some units follow a variable load programme with one or two large power changes per day as shown in Figures 1 and 2.

Load-following with Generation III/III+ reactors

The minimum requirements for the manoeuvrability capabilities of modern Generation III/III+ reactors are defined by the utility requirements[1] which are based on the requirements of the grid operators. For example, according to the current version of the European Utility Requirements (EUR), the NPP must be capable of a minimum daily load cycling operation between 50% and 100% P_r, with a rate of change of electric output of 3-5% P_r/minute.

Most of the modern designs implement even higher manoeuvrability capabilities, with the possibility of planned and unplanned load-following in a wide power range and with ramps of 5% P_r/minute. Some designs are capable of extremely fast power modulations in primary or secondary frequency regulation modes with ramps of several percentage points of the rated power per second, but within a narrow band around the rated power level.

Regulatory aspects of load-following with nuclear power plants

During the licensing process, an NPP's mode of operation is defined, and all types of transients are analysed. In France and in Germany, load cycling is explicitly defined in the operating handbook of the NPPs.

For example, in France the possibility of load-following is taken into account in the operating manual through a certain number of specific margins associated with operating in manoeuvring regime. To calculate these margins, a load pattern (corresponding to the needs of the grid) is defined for some reactors: about 12-18 hours at full rated power (P_r), 5-11 hours at 30% P_r and two times 30 minutes for the ramping (i.e. about 2.3% P_r/minute), up to 85% of the fuel cycle length. This type of load-following pattern has been used to perform thorough multi-disciplinary safety studies that are used to define the safety margins by the regulator.

Before a generic licence can be issued, experiments are performed on a selected unit to analyse operating experience and to validate the safety margins. Once the safety margins are established and the operating licence is issued, the utility commits itself to operate within these margins. In addition to the general license, some supplementary conditions regarding the fuel and the state of equipment (e.g. steam generators) must be fulfilled by the plants to obtain authorisation for manoeuvring. In some situations, the regulator can ask to suspend manoeuvring, for example if the physico-chemical characteristics of the core indicate a leak in a fuel element or other malfunction. The operating license also determines the maximum total number of load cycles based on the original design and the type of transient (magnitude and rate of power variation, etc.).

In some countries, there are explicit regulatory limitations on manoeuvring in the automatic mode. For example, according to the US Code of Federal Regulations (10 CFR Part 50), *"the licensee may not permit the manipulation of the controls of any facility by anyone who is not a licensed operator…" and "Apparatus and mechanisms other than controls, the operation of which may affect the reactivity or power level of a reactor shall be manipulated only with the knowledge and consent of an operator or senior operator licensed pursuant to part 55 of this chapter present at the controls".*

Although this does not prohibit power load variations controlled by the operator (if justified from the technical and economic viewpoints), manoeuvring in automatic mode is not authorised by current regulations in the United States.

Conclusions

Most of the currently operating Generation II nuclear reactors were designed to have strong manoeuvring capabilities. Nuclear power plants in France and Germany operate in load-following mode. They participate in the primary and secondary frequency control, and some units follow a variable load programme with one or two large power changes per day. In France, load-following is needed to balance daily and weekly power variations in electricity supply and demand since nuclear energy represents a large share of the national mix. In Germany, load-following became important in recent years when a large share of intermittent sources of electricity generation (e.g. wind) was introduced to the national mix.

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The economic consequences of load-following are mainly related to the reduction of the load factor. In the case of nuclear energy, fuel costs represent a small fraction of the electricity generating cost, especially compared to fossile sources. Thus, operating at higher load factors is profitable for nuclear power plants as they cannot make savings on fuel costs while not producing electricity. In France, the impact of load-following on the average unit capacity factor is sometimes estimated at about 1.2%.

Since most of the currently used nuclear power plants have strong manoeuvrability capabilities in their designs (except for some very old NPPs), there is no or limited impact (within the design margins) of load-following on the acceleration of ageing of large equipment components. However, load-following does have some influence on the ageing of certain operational components (e.g. valves), and thus one can expect an increase in maintenance costs. Moreover, for older plants some additional investment could be needed, especially in instrumentation and control, in order to become eligible for operation in load-following mode.

Licensing of load-following is specific to each country. In France and in Germany, for instance, load-following is considered early in the licensing process, and no further authorisation needs to be obtained by the utility to operate in manoeuvring regime. In other countries, load-following restrictions apply: for example in the United States, automatic load-following is not authorised.

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Philippe Lebreton, John Nakoski, Jan Keppler and Philippe Gress have provided valuable input and comments for this article.

Note

1. Utility requirements are defined in the Utility Requirements Document (URD) by the Electric Power Research Institute (EPRI) in the United States (EPRI, 2008), and in the European Utility Requirements (EUR) document in Europe (EUR, 2001).

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