

The Use of Nuclear Generation to Provide Power System Stability

Heather Wyman-Pain, Yuankai Bian, Furong Li

Abstract—The decreasing use of fossil fuel power stations has a negative effect on the stability of the electricity systems in many countries. Nuclear power stations have traditionally provided minimal ancillary services to support the system but this must change in the future as they replace fossil fuel generators. This paper explains the development of the four most popular reactor types still in regular operation across the world which have formed the basis for most reactor development since their commercialisation in the 1950s. The use of nuclear power in four countries with varying levels of capacity provided by nuclear generators is investigated, using the primary frequency response provided by generators as a measure for the electricity networks stability, to assess the need for nuclear generators to provide additional support as their share of the generation capacity increases.

Keywords—Frequency control, nuclear power generation, power system stability, system inertia.

I. INTRODUCTION

NUCLEAR power has been a popular choice for numerous countries since its commercialisation in the 1950s [1]. After accidents, such as Chernobyl, public opinion quickly opposed nuclear power and the building of new nuclear plants slowed.

In recent years, the focus on emission reduction has increased the popularity of nuclear power plants as a low carbon alternative, but there are still concerns over its safety and technical capabilities. Many countries have responded to safety concerns by increasing the regulation and requirements for nuclear reactors or not considering nuclear power as an alternative generation option for the future. The technical capabilities of nuclear reactors are changing as more investment is made into improving their ability to provide additional support to the systems they are within.

Traditionally nuclear generators have provided base load generation, with limited variation in their output during the day [2]. Their most economic operation occurs when they are providing a relatively consistent level of output, other generators providing variable generation to meet demand. This is the accepted situation in most countries where they have a wide portfolio of generation types and can choose to use them in their most economic ways. However, some countries, such as France, require nuclear to provide some load following capabilities and adjust their output during the day [3]. Increasing capacity from nuclear generators has made this into a global concern with investments being made into improving the flexibility of nuclear power stations.

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This paper is split into two main sections. Section II explains the initial creation of the four main reactor types and their different capabilities. The next section, Section III, investigates the primary frequency response provided by generation in four countries, both with and without a contribution from the nuclear generators.

II. REACTOR DEVELOPMENT

A. Reactor Priorities and Functions

During the development of nuclear reactors there are several aspects to consider. These include the primary reason for investment in nuclear reactors (a cleaner power source, proving technological capabilities or the creation of material for nuclear weaponry), the capabilities of manufacturing within the country and the availability of materials involved within the design. This has caused a wide range of reactor types to be developed, of varying success, across the world and a limited number are still in use today.

America were leaders in the design and development of nuclear reactor technology [1], creating the Pressurised Water Reactor (PWR) and Boiling Water Reactor (BWR) before selling their designs to other countries. They were focused on using a new power source to generate electricity, having demonstrated the energy found in fissionable material previously, and had access to refined fissionable material as well as advanced manufacturing techniques. This enabled them to develop progressive designs, compared to other countries, which are the basis for the two most popular reactors still in use today.

The Canadians had limited manufacturing processes and were unable to produce the large reactor chambers required for the American designs [2]. This forced them to develop their own reactors, the CANDU reactor, which made use of the Canadian manufacturing capabilities and their access to certain materials, such as heavy water. The Canadians also noted a failing of the American designs, the inability to refuel whilst the station was running, and ensured their reactors would be capable of reloading whilst in operation.

The UK had limited resources, when compared to America and Canada, to build nuclear reactors so had to design them with a different focus [4]. This resulted in gas cooled reactors due to the lack of access to heavy water or refined fissionable material. These designs lacked the efficiency found in water based reactors and has potential safety issues of carbon blocks within the core which has made the design less popular. However the lower resource requirements, ability to refuel whilst on load and not requiring refined fuel to operate make

it a suitable option for countries with less access to certain resources.

France is a more recent player in the development of nuclear power [5]. They have invested in enhancing the capabilities of PWRs, focusing on the manoeuvrability and economical operation of the reactors. Although initially using gas cooled reactors, they switched to PWRs and developed the European Pressurised Water Reactor. They are currently designing a variety of generation IV reactors which will provide low carbon electricity in the future, but the prototypes are still in the early stages so their success has not been demonstrated.

B. Reactor Types

There are many different reactor types in use across the world today. The basis for the majority of these are four initial designs which were developed to harness this new energy source.

1) *Pressurised Water Reactor (PWR)*: This is the most common type of nuclear reactor and is in use across the Globe [6], since it went into commercial operation in 1957 [7], [8].

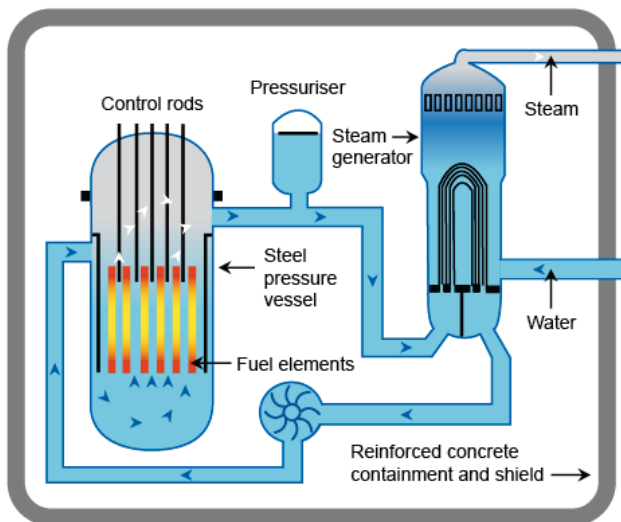


Fig. 1 Pressurised Water Reactor [2]

The steam generated by the heat from the core is used to turn a steam generator and produce electricity, as in typical thermal generators, and shown in Fig. 1. Within PWRs there are two coolant systems; the first remaining within the containment shield and held under pressure to prevent steam pockets forming, whilst the second interacts with the first coolant cycle through a heat exchanger and generates steam to leave the containment shield. In most PWR systems both coolant cycles are filled with water; heavy water is preferred as it is a superior moderator but is an expensive commodity, so light water tends to be used as the alternative in most situations.

The main methods of controlling the PWR in large scale energy production are by using control rods and the addition of boric acid to the primary coolant [3], [9]. In modern designs there are two types of control rods used: black which absorb significant numbers of neutrons and can quickly cause a drop

in reactivity within the core, and grey which have a lower absorption level first introduced in 1981 known as mode G. This allows finer control of the reactivity within the core and less potential to cause an instability with the greater spread of neutron absorption. Using boric acid is less popular in modern plants due to the environmental impact it has. The speed of the response is too slow to take part in load following without high concentrations being introduced that require the coolant to be scrubbed clean rather than being burnt away. The main benefit of using a poison is the effect it has is spread across the entire core evenly, preventing instabilities where the reactivity is concentrated in small areas.

2) *Boiling Water Reactor (BWR)*: The BWR is the second most common reactor type in the world with 35 in use in the USA [6]. They were first developed in the USA by Idaho National Laboratory and General Electric as an alternative to the PWR in the late 1950s [10], [11].

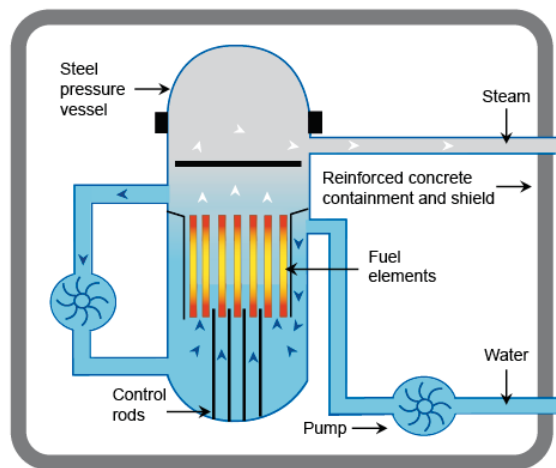


Fig. 2 Boiling Water Reactor [2]

The main difference between the PWR and the BWR is the lack of a heat exchanger. There is only one coolant cycle which creates the steam within the reactor core and sends it straight to the turbine. As implied within the name, water is needed as a coolant and it depends on availability as to whether heavy or light water is used.

To control the output of BWRs control rods can be used, as with PWRs, and most modern reactors contain black and grey banks to maintain the desired outputs. They also use the flow rate of the coolant to affect the output of the reactor but do not add any boric acid to the mixture. As the flow rate drops more steam builds up in the core reducing the reactivity, if the void coefficient is negative, and the output power of the reactor is lowered.

3) *Advanced Gas Cooled Reactor (AGR)*: The gas cooled reactor was developed in the UK [12] as part of a scheme to demonstrate the engineering success of the nation, both in power generation and nuclear weapons production, whilst the USA was investing in developing their own reactor technology. The AGR is based on the original gas-cooled reactor designs, called MAGNOX as the fuel rods were coated in a layer of

magnesium oxide, which are now obsolete but proved the American built systems were not the only option for reactor technology [4], [13].

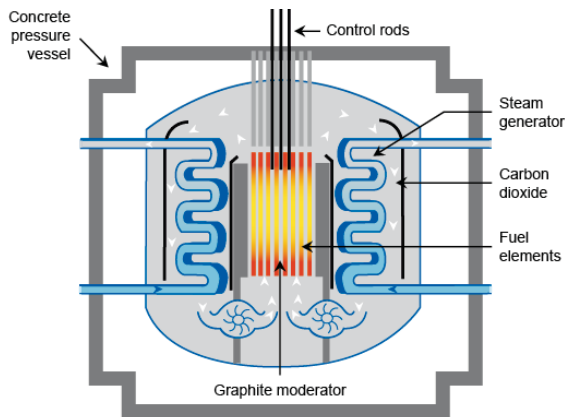


Fig. 3 Advanced Gas-Cooled Reactor [2]

Although the AGR may appear significantly different from the PWR and BWR the key operational features are still the same. A primary and secondary coolant are present which operate using a heat exchanger to generate steam for the turbines and control rods are used to maintain a stable core. However the primary coolant is a gas, usually carbon dioxide but helium is also a possibility, which is circulated around the core and the secondary coolant flows through pipes which are brought within the inner reactor vessel, though not into the core.

In PWRs and BWRs, the coolant water is also used to moderate the neutrons, which is impossible within an AGR as gases do not make successful moderators. Instead other moderating substances must be introduced and the common choice is graphite. This can be a dangerous choice if the core does not remain free of oxygen as graphite will combust at temperatures far below those experienced within the core in the presence of oxygen.

Another major difference between the AGR and the previous two reactor types is the ability to refuel when on partial load. This was considered a priority when designing the MAGNOX reactors, which could refuel when on full load to minimise the need for the plant to be brought offline. The new AGRs could potentially be refuelled whilst on full load, but due to safety concerns they are now reduced to partial load before any changes are made to the fuel.

4) *CANDU*: Canada was the second country to invest in nuclear generation, and had their first successful test in 1945 [14], [15]. They, like the UK, invested in developing their own reactor design rather than copy the American options and created the CANDU (CANadian-Deuterium-Uranium) reactor [16], [17].

When the Canadians were investing in nuclear generation, their manufacturing industry was limited, meaning a large pressure vessel to house the reactor core was impossible to create which could withstand both the heat and coolant circulation. This resulted in a core which was separated into

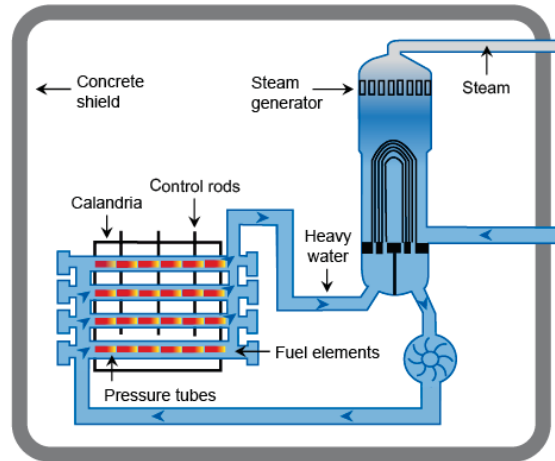


Fig. 4 CANDU Reactor [2]

several small pipes, as shown in Fig. 4, each containing several fuel elements and the coolant circulated around them. As with the PWR this coolant is then sent through a heat exchanger to form steam in the secondary coolant system. The main benefit of keeping the design with tubes instead of a large pressure vessel is that each tube can be shut down individually and the fuel elements replaced remotely whilst on-load. This can also mean if one tube gets damaged it will not require a plant shutdown to be done immediately to fix the problem. Although the manufacture of large pressure vessels was unable to be done, the production of heavy water was possible during the development of this design and has remained a key feature when the design was exported to other countries.

III. COUNTRIES USING NUCLEAR GENERATORS

Many countries continue to use nuclear generators as a significant part of their generation mix and an important alternative to fossil fuels for large scale electricity generation with lower carbon footprints. Some of these countries are described in this section and their choice of reactor type explained.

The contribution to primary frequency response from their generators is found from initial models to demonstrate the stability achieved by this generation mix, but additional support is found from other systems with AC connections to the area considered, the part loading of generators and synchronous demand. All simulations used in this section assume a demand of 50 GW, a loss of 1.8 GW and the primary response provided by each generation type is an approximation as each generator will respond differently due to technical and operational limitations specific to that generator.

In each country the frequency analysis is run with and without nuclear generators providing a response to demonstrate the difference this can make. Most systems have limits on the frequency deviation permitted during normal operation, for example the UK has statutory limits of 49.5 Hz to 50.5 Hz and operational limits of 49.8 Hz to 50.2 Hz [18].

A. America

The USA has continued to use nuclear power stations as a significant part of their energy mix since their commercial introduction in 1957. There are numerous nuclear reactors across the States, with the majority in the Eastern half of the USA, with new reactors approved to replace those being retired. The USA has remained focused on PWR and BWR designs since they were developed, but is investigating new designs involving liquid metal and gases as coolants for the next generation of nuclear reactors [2].

Some states, such as California, are using nuclear as a low carbon option to include as they replace their fossil fuel generators. The capacity provided by different generator types in 2014 are shown in Fig. 5 but priority to operate is given to renewable generators over the fossil fuelled options.

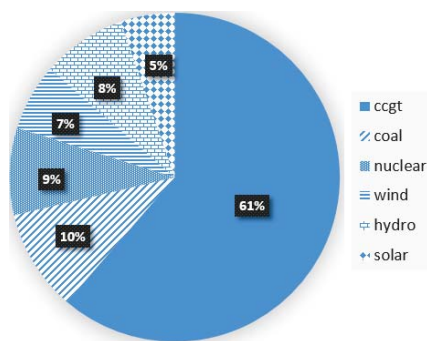


Fig. 5 Generation Mix of California in 2014 [19]

TABLE I
PRIMARY FREQUENCY RESPONSE IN CALIFORNIA

	With Nuclear Response	Without Nuclear Response
Initial Rate of Change of Frequency - Hz/second	0.087	0.093
Generation Inertia - p.u. second	6.45	5.94
Minimum Frequency - Hz	49.51	49.46

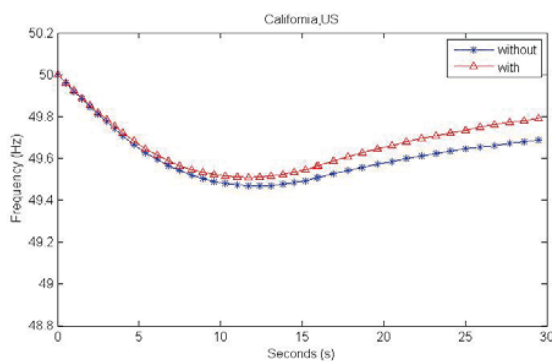


Fig. 6 Primary Frequency Response for California, US

As shown in Table I and Fig. 6 the frequency drops to 49.46 Hz without nuclear providing primary response and

49.51 Hz with nuclear. Although these values drop below the operational limits of the UK, and without nuclear response the frequency drops below the statutory limits as well, the inclusion of primary responses from other sources will keep it within the limits. The use of nuclear power plants to provide primary response is not essential to maintain a stable system with the generation mix shown, but as fossil fuel generators continue to decrease this may change.

B. Canada

Canada has significant levels of renewable generation options available due to their geography which has enabled them to limit their fossil fuel and nuclear energy usage. Hydro generators are the most popular generators in Canada, nearly 60% of their total capacity was from hydroelectric sources in 2014, whilst fossil fuels and nuclear are the main alternatives in the majority of network areas.

In Ontario, as shown in Fig. 7, nuclear is the dominant source of electricity, with gas and hydro also providing significant proportions of the total capacity.

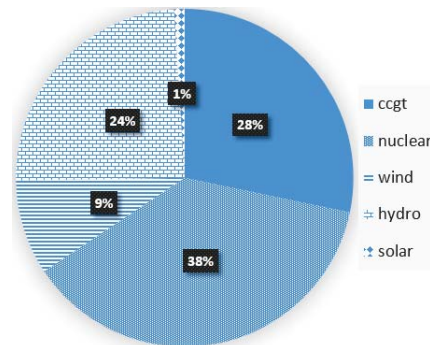


Fig. 7 Generation Mix of Ontario in 2014 [20]

TABLE II
PRIMARY FREQUENCY RESPONSE IN ONTARIO

	With Nuclear Response	Without Nuclear Response
Initial Rate of Change of Frequency - Hz/second	0.088	0.114
Generation Inertia - p.u. second	6.41	4.53
Minimum Frequency - Hz	49.40	49.26

Despite the increase in nuclear penetration, above that seen in California, the minimum frequency reached is not significantly below the statutory limit, as shown in Table II and Fig. 8, reaching 49.26 Hz without nuclear providing primary response and 49.40 Hz with nuclear. Ontario is connected to numerous other transmission systems in both Canada and the USA which will provide an increase in the system stability, as well as the primary frequency support provided by synchronous demand. The use of nuclear power plants to provide primary response is not essential in this system, but may be required as the contribution provided by fossil fuels is replaced by renewable resources.

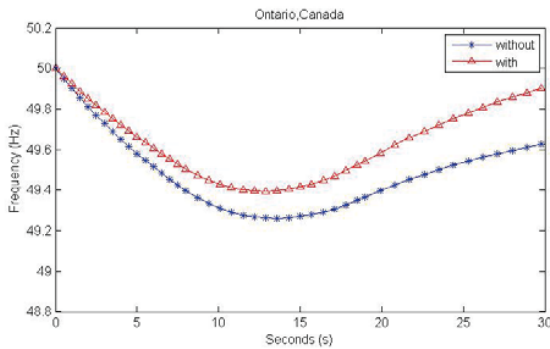


Fig. 8 Primary Frequency Response for Ontario, Canada

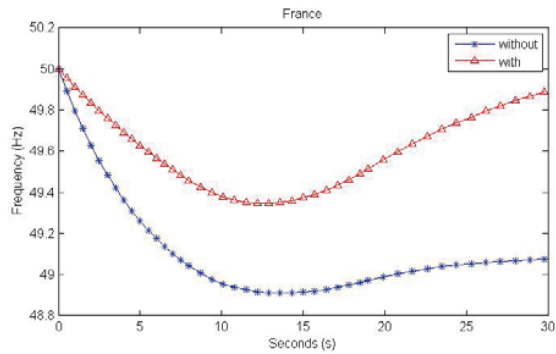


Fig. 10 Primary Frequency Response for France

C. France

Due to the high levels of nuclear power in France, as shown in Fig. 9, these generators must adjust their output during the day. This has forced them to choose which plants to provide which services dependant on their position in the fuel cycle, which can last between 18 and 24 months, or their operational restrictions [3].

- First 65% of the fuel cycle load following and frequency response is required
- 65% to 90% of the fuel cycle minimal changes are made to adjust the output, except during significant variations between generation and demand
- Last 10% of the fuel cycle or restricted plants will only perform emergency shut downs to ensure the safety of the plant

Most of the plants performing load following will follow an approximate schedule of 100% output during the day and 50% overnight and weekends depending on the predicted demand.

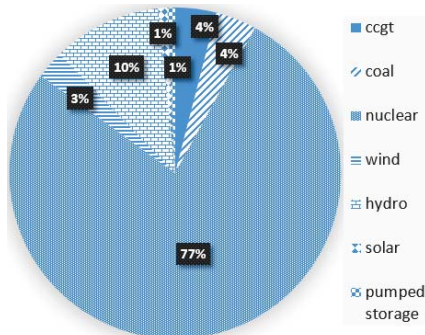


Fig. 9 Generation Mix of France in 2014 [21]

With the significant levels of nuclear generation found in France the minimum frequency reached without a primary frequency response contribution from nuclear generators is 48.91 Hz and 49.35 Hz with all nuclear generators contributing. These values are below the statutory limits but, as with California and Ontario, there are contributions from synchronous demand and other transmission systems. However with such a high nuclear contribution it is essential that some, or all, nuclear power stations provide a contribution to the primary frequency response.

D. UK

The UK has continued to use AGRs as part of their generation capacity, but are investing in new PWRs and BWRs for the future. The percentage capacity provided by nuclear is below that found in Ontario and France but the UK, unlike the other three systems, only has DC interconnectors so receives no support from outside systems to maintain the frequency. They still have a contribution from synchronous demand so the minimum frequency values achieved will be lower than those found in the real system.

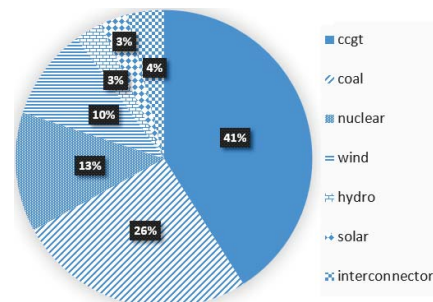


Fig. 11 Generation Mix of UK in 2012 [22]

TABLE III
PRIMARY FREQUENCY RESPONSE IN FRANCE

	With Nuclear Response	Without Nuclear Response
Initial Rate of Change of Frequency - Hz/second	0.238	0.099
Generation Inertia - p.u. second	5.51	1.13
Minimum Frequency - Hz	49.35	48.91

The minimum frequencies of 49.37 Hz with nuclear contributing, and 49.31 Hz without, are between the two values found in Ontario and below the statutory limits required in the UK. As this level of generation loss is considered an extreme frequency event, and the model does not include the contribution from synchronous demand, exceeding the statutory limits is acceptable, but not ideal. Including primary

TABLE IV
PRIMARY FREQUENCY RESPONSE IN THE UK

	With Nuclear Response	Without Nuclear Response
Initial Rate of Change of Frequency - Hz/second	0.092	0.101
Generation Inertia - p.u. second	6.02	5.30
Minimum Frequency - Hz	49.37	49.31

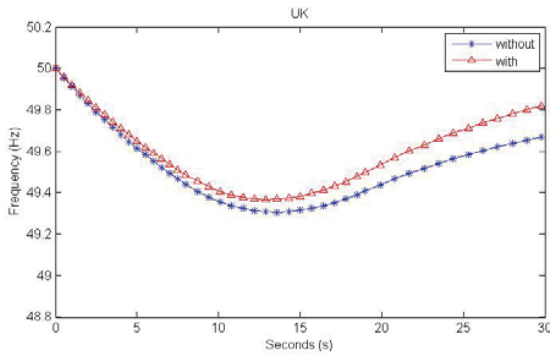


Fig. 12 Primary Frequency Response for the UK

frequency response from nuclear shows a clear benefit in maintaining system stability.

E. Role Within a Low Carbon Generation Mix

As explained in earlier sections, nuclear has traditionally been considered as a base load provider, but that is changing as many countries move towards low carbon options. As the level of fossil fuel power stations decreases the requirement for alternative providers of primary frequency response will increase, as shown in the primary frequency response across the world, and nuclear generators will need to take an active role. They are already performing this in France to ensure system stability, but it is required in systems dominated by renewable and nuclear generators.

IV. CONCLUSION

Nuclear generation is increasing in many countries as they retire their fossil fuel generators. As this nuclear penetration increases the services, including primary frequency response, must be provided by an alternative technology, nuclear or renewable generators to ensure a stable system.

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