Study on the Fuel Cell as an Standby AC Power Source of Nuclear Power Plants

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1. Introduction

The alternation standby AC power for nuclear power plants includes emergency generators and alternative AC generators. Two 8,000kW safety class emergency generators and one 700kW emergency generator have been installed at each of the recently completed Shin Kori Units 3 and 4. In addition one 7,200kW non-safety class alternative AC generator has been installed for both units[1].

The purpose of this paper is to study the feasibility of replacing the diesel generators, which are mainly used in the existing AC standby power sources, with fuel cells. The expected effects of replacing existing diesel generators with fuel cells prior to full-scale research are first to increase diversity of the standby AC power and second to supply the high voltage system that can be operated as the uninterruptible power supply.

2. Requirements for Standby Onsite AC System

In order to utilize fuel cells as standby AC power for nuclear power plants, the characteristics of the onsite standby AC power and the requirements to be met should be reviewed first.

2.1 Reliability and Availability

In the event of loss of offsite power (LOOP) of the APR1400 plant, the emergency generator shall provide power to the safety bus within 20 seconds. If the emergency generator fails operation, alternative AC power shall be applied within 10 minutes. The emergency generator shall be capable of supplying power in the event of any postulated accident or event. Emergency generators are major variables that affect the risk of reactor meltdown due to SBO. The emergency generator shall have sufficient capacity in case of design basis accident, have been validated by the device, and have the required level of reliability and validity[2]. The reliability of the emergency generator shall be at least 0.98 based on successful startup and successful load operation. If the LOOP period is prolonged, it should be able to continuously supply power during that period (e.g. refuel every seven days and drive for 30 days).

2.2 Independence

Where power is supplied from the standby power source, the redundant load group and the redundant standby power shall be independent of each other[3]. The standby power of one group of loads shall not be automatically parallel to the standby power of the other load group upon accident. Devices that automatically connect one load group to another should not be installed, and devices that can transfer loads between the load groups should not be installed. If there is a device that manually connects the independent load group together, at least interlocks shall be installed so that the driver does not inadvertently parallelize the redundant power unit.

2.3 Starting and Operation

Emergency power shall be capable of sequentially starting large motors at regular intervals while keeping voltage and frequency within the allowable range. The large motor start voltage shall be not less than 75% (or ESF Motors) or 80% (for BOP motors) of the rated voltage of the motor. Voltage drop analysis shall be performed to prevent trip of specific loads during sequential motor start-up. The rated speed of the large induction motor can be achieved within 5 seconds if power is supplied from the diesel generator of the proper specification that can restore the rated voltage of the bus to 90 % within 1 to 2 seconds after startup.

3. Alternatives of Emergency Power Generator

3.1 Diesel Generator

Currently, all the standby AC power generator of the local nuclear power plants are diesel generators, with a generating capacity of approximately 5,000 kW to 8,000 kW. Diesel generator means a generator that combines an internal combustion engine with a synchronous generator. Diesel generators produce AC power for nuclear power plants as long as fuel is supplied, and they are highly durable and reliable. Since diesel generators are widely used as standby power generator, they are also more economical than other types of generators. Especially, operation cost is lower than natural gas generators because fuel supply is easy and the price is low. In contrast, diesel generators are high speed rotators, so they are noisy and relatively difficult to maintain. Also, the use of fossil fuels makes it a disadvantage due to release of pollutants.

3.2 Gas Turbine Generator

In some cases, diesel generators are used as emergency AC power in nuclear power plants and gas turbines are used as alternative AC power source. This is to increase the diversity of AC standby power. The greatest advantage of gas-fueled generators is less pollutants emissions such as sulfur, nitrogen, and carbon dioxide (a greenhouse gas) than diesel generators. On the management side of the generator, there is a high risk of fire compared to diesel oil, while diesel oil is prone to leak.

3.3 Fuel Cell

Fuel cell refers to power generation device that convert chemical energy into electrical energy by electrochemical reactions of hydrogen and oxygen. When hydrogen and oxygen react within fuel cells, what is different from conventional generators is that they produce water, electricity, and heat directly through the non-combustion electrochemical reactions without undergoing through the combustion process. Therefore, considering the technology of fuel cells only, fossil energy is not used as the source of power generation, but rather the use of hydrogen which is a very eco-friendly power generation technology with no combustion process[4].

4. Configurations of Fuel Cell Emergency Power System

4.1 Principles of Operations

The fuel cell is a device that converts chemical energy into electrical energy using the electrochemical process. The chemical reactions of typical fuel cells are shown in Table 1[5].

Table 1 Electrochemical Reactions in Fuel Cells

Fuel Cell	Anode Reaction	Cathode Reaction
Polymer Electrolyte and Phosphoric Acid	$H_2 \rightarrow 2H^+ + 2e^-$	$\frac{1}{2} O_2 + 2H^+ + 2e- \rightarrow H_2O$
Alkaline	$H_2 + 2(OH)^- \rightarrow 2H_2O + 2e^-$	$\frac{1}{2} O_2 + H_2O + 2e- \rightarrow 2(OH)^-$
Molten Carbonate	$H_2 + CO_3^= \rightarrow H_2O + CO_2 + 2e-$ $CO + CO_3^= \rightarrow 2CO_2 + 2e-$	$\frac{1}{2} O_2 + CO_2 + 2e- \rightarrow CO_3$
Solid Oxide	$H_2 + O^= \rightarrow H_2O + 2e-$ $CO + O^= \rightarrow CO_2 + 2e-$ $CH_4 + 4O^= \rightarrow 2H_2O + CO_2 + 8e-$	$\frac{1}{2} O_2 + 2e^- \rightarrow O^=$

This electrical energy can be used to supply vehicles, electronic devices, homes, or electrical grids. More attention has been given to fuel cell technology because of its high efficiency and clean process over the past decades. As a battery that stores energy, fuel cells convert the chemical energy of the fuel supplied into electrical energy without using the energy stored within the structure. Fuel cells differ from conventional heat engines in that they produce electricity directly from chemical energy without converting to mechanical power in the intermediate stage. The only byproduct of fuel cell operation when hydrogen is used as fuel is water and heat.

4.2 Types of Fuel Cell

The fuel cell is divided into low and high temperature types. Low-temperature fuel cells are again divided into polymer electrolyte membrane fuel cells (PEMFC) and phosphate acid fuel cells (PAFC). Polymer electrolyte membrane fuel cells are mainly used for household and transport, while phosphoric acid fuel cells are mainly used for buildings. High-temperature fuel cells, molten carbonate fuel cells (MCFC), are mostly used for power generation, while solid oxide fuel cells (SOFC) are in the development and demonstration phase of technology prior to commercialization Table 2 shows the major difference of the fuel cell types[5].

Table 2 Summary of Major Differences of the Fuel Cell Types

Description	PEMFC	PAFC	MCFC	SOFC
Electrolyte	Hydrated Polymeric Ion Exchange Membranes	Immobilized Liquid Phosphoric Acid in SiC	Immobilized Liquid Molten Carbonate in LiAlO2	Perovskites (Ceramics)
Electrode	Carbon	Carbon	Nickel and Nickel Oxide	Perovskite and perovskite / metal cermet
Catalyst	Platinum	Platinum	Electrode material	Electrode material
Operating Temperature	40 – 80 °C	205 °C	650 °C	600-1000 °C
Utilization	Household/ Transport/ Portable	Household/ Buiding/ Backup Power	Generation/ Building/ Backup Power/ Ship	DG/ Building/ Backup Power
Capacity	<1 kW ~1 MW	50 kW ~1 MW	100 kW~ 10 MW	5 kW – 3 MW
Efficiency	34 ~ 36 %	40%	47~62%	45~65%

Fuel cells used mainly for power generation in Korea are mostly MCFC and PAFC while PEMFC is for household use. PEMFCs are suitable for small distributed power sources as they can be regulated according to demand patterns, whereas MCFCs and PAFCs need to be continuously operated and are used for power generation for buildings.

4.3 Equivalent Electrical Circuit of Fuel Cell

From Fig. 1[6], the output voltage of a fuel cell can be written as

$$V_{cell} = E_{cell} - V_{act,cell} - V_{ohm,cell} - V_{conc,cell} \quad (1)$$

where V_{cell} and E_{cell} are the fuel cell output voltage and internal voltage respectively, and $V_{act,cell}$ is activation voltage drop, $V_{ohm,cell}$ is ohmic voltage drop, and $V_{cone,cell}$ is concentration voltage drop.

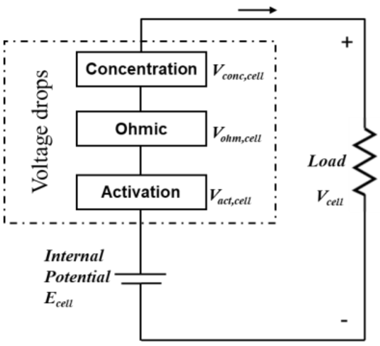

Fig. 1 Fuel cell equivalent circuit

The ohmic resistance ($R_{ohm,eell}$) is normally a function of fuel cell temperature. The activation and concentration voltage drops are nonlinear functions of load current as well as pressure and/or temperature inside the fuel cell.

4.4 Dynamic Model

In addition to the load current, pressure and temperature of the fuel cell, the fuel cell's charge storage capability also affects the dynamic response. Therefore, the fuel cells have the characteristics to the "capacitance of double-layer charge effects." Fig. 2 shows equivalent circuit of the double-layer charging effect inside fuel cells[6]. R_{act} is activation resistance, and the internal voltage is defined as E-V_{aet1}. V_{act1} is the temperature-dependent part of V_{act} and V_{act2} is both current and temperature dependent. R_{conc} is the equivalent resistance of concentration voltage drop, which can be calculated according to (2).

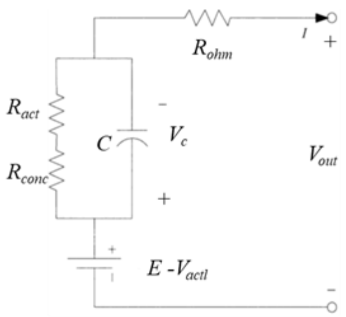

Fig. 2 Equivalent circuit of the double-layer charging effect inside a PEMFC

$$R_{con} = \frac{V_{con}}{I} \tag{2}$$

$$R_{act} = \frac{V_{act2}}{I} \tag{3}$$

$$V_c = (I - C^*dV_c/dt)(R_{act} + R_{conc}) \tag{4}$$

The double-layer charge effect is integrated into the modeling, by using V_c for calculating V_{out}. From Fig. 2, the fuel cell output voltage can be written as follows:

$$V_{out} = E - V_{act1} - V_c - V_{ohm} \tag{5}$$

4.5 Fuel Cell backup Emergency Power System

The schematic diagram of the medium voltage bus-connected FC emergency power system is shown in Fig. 3. [6].

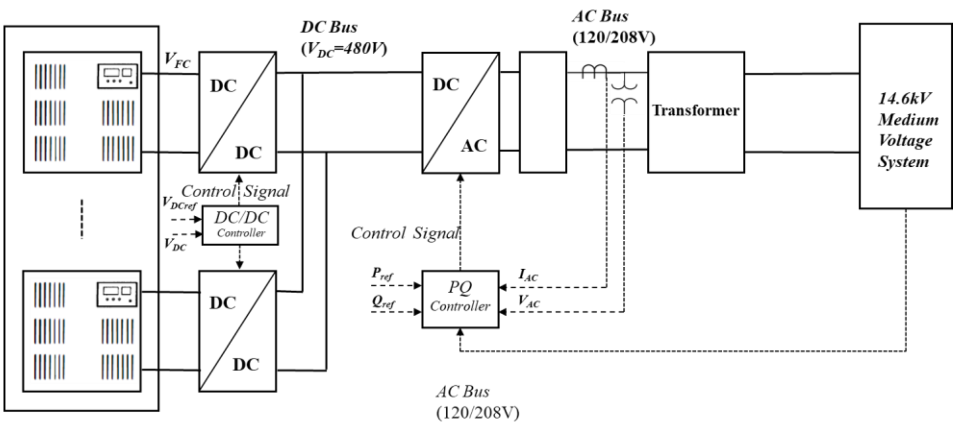

Fig.3 Block diagram of fuel cell backup emergency power system

The FC power system in the figure can either be PAFC or SOFC type.

4.6 Present Challenge

4.6.1 Hydrogen Supply

Methods for producing hydrogen include to refine natural gas, to extract from coal, to use nuclear energy, to electrify water, and to use biomass. The way to extract H_2 from natural gas is the most economical at present. In the United States, more than 90% of H_2 production is made using steam methane. Coal has abundant potential for H_2 production. The process of coal gasification is similar to that of thermal power generation. The downside, meanwhile, is that CO_2 generates the most. Methods for production of H_2 using the nuclear reactor include methods of electrolysis and thermochemical treatment. Electrolysis is an effective H_2 production method by raising the water temperature to 700°C to

1000°C. Since LWR operates at 350°C or below, it is more economical to supply heat to the steam methane reformation process compare to the water electrolysis method. Electrolysis is a method used mainly to produce hydrogen needed in chemical plants through separation of hydrogen and oxygen from water molecules. However, production costs are higher than those of steam reforming or natural gas conversion. In the case of a compressed hydrogen method, the container is highly priced due to the high charging pressure, and there is a disadvantage of requiring a separate charging station. Liquefied hydrogen requires extremely low temperature, requires a separate cooler, and there is a problem where hydrogen is boiling-off after becoming charged[7].

4.6.2 Reliability

Fuel cells can be strategically placed at any site in a power system (normally at the distribution level) for grid reinforcement, deferring or eliminating the need for system upgrades, and improving system integrity, reliability, and efficiency. Performance, reliability, durability, fuel availability and cost should be considered in order to use the fuel cell power unit as a standby power source, and particularly the primary concern is reliability. In particular, target reliability of 0.95 or 0.975 is required to use as an emergency power system of nuclear power plants.

4.6.3 Response characteristics

PEMFCs can operate at low temperatures (50~100°C), which enables a fast start-up. Hence, PEMFCs are particularly attractive for transportation applications that require rapid start-ups and fast dynamic responses over transient times (stopping and running, acceleration, and deceleration [8].

The fuel cell system needs to be equipped with a battery system to start-up or to supply peak load demand. This secondary power source can be charged during the steady states from the fuel cell system and be discharged during the transient period when the fuel cell system responds to sudden load changes.

4.6.4 Economic feasibility

There are several types of fuel cells, but if only economic considerations are taken into account, high-temperature fuel cells such as solid oxide fuel cells (SOFC) and molten carbonate fuel cells (MCFCs) are suitable for high-capacity power generation facilities[9]. Ultra-high temperature reactors (VHTRs) are very effective in cogeneration that produce both electricity and hydrogen at the same time, and hydrogen is extracted from water using thermochemistry, electrochemical or hybrid processes.

5. Discussions

As described in Sect.2, the standby AC power of the nuclear power plants require the reliability and quick response time and ease of fuel supply. In addition, safety related equipment shall be seismically and environmentally qualified. Therefore, the problem of stable supply and storage of hydrogen fuel should be solved. For example, if VHTR is commercialized, self-produced hydrogen can be used as fuel. The reliability and performance will likely be satisfied gradually with the spread of fuel cells. The issue of equipment qualification is the same.

6. Conclusions

The suitability of fuel cells as standby AC generation systems of nuclear power plants was reviewed. Given the above findings, the use of fuel cells in the nuclear power plants can be considered in two aspects. First, fuel cells may be used as standby AC power sources, such as emergency generators and AAC generators. For this purpose, the security of hydrogen supply shall be assured, and the starting time and stability are critical factors to be met by the backup power system. Therefore, further study will be continued for the above issues. Research on how to construct an effective electrical device and circuit will also be carried out simultaneously.

Second, the reactor produces hydrogen from heat produced during low demand times, and then produce electricity by the fuel cell during the peak load. Research on this approach should also be actively conducted, as the share of renewable energy, a variable resource, will increase significantly by 20 percent in 2030.

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