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Performance evaluation of an independent microgrid comprising an integrated coal gasification fuel cell combined cycle, large-scale photovoltaics, and a pumped-storage power station

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A B S T R A C T

Integrated coal gasification fuel cell (IGFC) combined cycle has significant advantages in power generation efficiency and reduced environmental impacts. Use of IGFCs for coal has increased throughout the world, and its power generation efficiency is higher than that of a conventional combined cycle. This study presents a method of applying a system comprising renewable energy, pumped-storage power generation, and IGFC as an independent microgrid. The IGFC is examined for its use as base load supply with a constant output. Potential technologies for interconnection with renewable energy have only recently begun to be investigated. This study proposes an operational method for stabilizing electric power supply and demand by adjusting the daily output of the IGFC and adjusting the input and output of the pumped-storage power station for each sampling period. Furthermore, when the proposed microgrid was introduced into the power load pattern on a representative day in Hokkaido, Japan, the relation between the load factor of the IGFC and the power generation efficiency of each power source was clarified. Moreover, the economic efficiency of the proposed IGFC and integrated gasification combined cycle was investigated, and the operational advantages of the IGFC were clarified.

1. Introduction

The Japanese power industry will be completely deregulated from April 2016, after which the expansion of the distributed energy system by local utilities is expected. For the next generation of electric power systems in Japan, a mix of conventional concentrated electric power and a new distributed energy system is anticipated. Although an interconnection between other electric power systems and an independent system to form a distributed energy system is possible, any distributed energy system can make effective use of the exhaust heat from an electric power plant. It is necessary to stabilize power fluctuations resulting from renewable energy use and the load within an electric power system in a distributed energy system. Control of the supply–demand balance at a high speed requires control technology for the power source. However, when electric power fluctuations are controlled by a thermoelectric power plant and the load factor of the power source is changed, a drop in the efficiency of partial load operations occurs.

Control of the power change to renewable energy using pumped-storage power generation (PSPG) has been investigated in Japan. Introduction of a combined cycle with Japanese coal gasification technology was expected [1]. Recently, several approaches were implemented for development of the combined power system with coal gasification in Japan: integrated gasification combined cycle (IGCC) demo plant [2]; clean coal technologies, such as USA, Japan, and Italy [3]; and energy flow of advanced IGCC [4]. In the integrated coal gasification fuel cell (IGFC) combined cycle, hydrogen produced by coal gasification is supplied to a solid oxide fuel cell (SOFC) and a gas turbine (G/T) is operated using the exhaust heat and unused hydrogen of the SOFC. Use of the IGFC to operate a steam turbine using the exhaust heat from the G/T is extremely promising with regard to power generation efficiency and reduction of environmental impacts: production of pure H_2 from gamified coal and capture the main part of the generated CO_2 [5]; system analysis of IGFC with exergy recuperation [6]; steam co-gasification using biomass and coal [7]; greenhouse gas abatement

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cost of hydrogen production [8]; and economic evaluations of gasification power plants [9]. With efficiency higher than the conventional combined cycle, the power generation system with coal gasification is expected to become the key technology of future thermal power generation. Although it is possible that the maximum gross thermal efficiency of the IGFC reaches 70%, the IGFC is considered to be the base supply for uniform output power. Many performance evaluation of SOFC, IGFC, and IGCC and reduction of the environmental impact have been reported: prospect of low-temperature operation of SOFC [10]; evaluation of substitute natural gas production from coal gasification [11]; economic analysis of advanced IGCC and IGFC [12]; economic performance of novel IGFC with carbon capture [13]; and water–gas shift using synthesis gas from coal gasification [14]. With regard to the output adjustment using the governor control of the IGFC, example of a relevant investigation has not yet been identified. In this study, the power generation efficiency of the proposed system with the daily output adjustment is clarified by modelling of the IGFC. Moreover, regarding the system that introduced the IGFC as a base power source for an independent microgrid using photovoltaics and PSPG, the operational method and the initial capacity of equipment based on cost minimization are clarified. As the output adjustment of the IGFC takes several hours [15], the output power of photovoltaics and the power demand for a representative day are predicted on the previous day. Operation of the IGFC (uniform output power) on the representative day is planned on the basis of the prediction results.

Most initial examples of an independent IGFC microgrid have not been reported, and there is little documented research on the interconnection with renewable energy [16]. Therefore, the economic efficiency of the independent microgrid with the daily output adjustment of the IGFC based on supply and demand and the time shift of electricity using PSPG is confirmed. Concerning the proposed microgrid with a power load pattern on a representative day in Hokkaido, Japan, numerical simulation was conducted to compare the cost when IGFC or an IGCC is installed. Moreover, optimal facility planning and the operation method for assessing power generation efficiency and cost are clarified. Based on these results, the effects of the IGFC independent microgrid is investigated.

2. Materials and methods

2.1. Overview of the system

2.1.1. Components

Fig. 1 shows the configuration of the proposed independent microgrid using an IGFC applied to a small-to-medium-size city. A large-scale solar power station, PSPG, and IGFC are interconnected, and electric power is supplied through a substation. Although the IGFC is operated using constant daily load, the demand-side power load and the output from photovoltaics are predicted on the previous day. The output power of the IGFC converts the supply–demand difference for each sampling time using PSPG. Moreover, the capacity of each device is determined based on the goals of minimizing fuel and equipment costs. The IGFC is used as a source of uniform daily base power output, and the PSPG provides a source of peak power to be reflected in the supply–demand change. When the power output of the photovoltaics is high, or when the power load is low, a less efficient partial load operation occurs in the IGFC. Therefore, in this study, the power generation efficiency of the whole IGFC was obtained by modelling the relation of efficiency and load factor of a coal gasifier, an SOFC, a G/T, and a steam turbine (S/T). Together, these comprise the IGFC and provide a load factor for use in the model equations.

2.1.2. Operational method

Fig. 2 shows the operational method for the proposed system on a representative day. Fig. 2(a) shows the method using photovoltaics. Fig. 2(b) shows the method with the output power of photovoltaics. The operational plan for the IGFC predicts the power demand and the output of the photovoltaics on the day before the representative day. By predicting the results using the analytic algorithm of the operational method, the output power of the IGFC on the representative day can be determined. As the IGFC operates with uniform output power on a representative day, the power outputs of the SOFC, G/T, and S/T introduced into the IGFC are constant. The surplus power load is used for pumping up of the PSPG. Fig. 2(a) and (b) show that when the power load of the IGFC and photovoltaics is insufficient, the supply–demand balance is maintained by the power output of the PSPG. The optimal capacity of the large-scale solar power system, PSPG, and IGFC in the independent microgrid is determined. In addition, the system's operational method is determined using an analytic algorithm. Moreover, the power generation efficiency, fuel cost, and equipment cost of the proposed microgrid are clarified.

2.1.3. Operation of the system under partial load

Fig. 3 shows the system configuration of the proposed IGFC. This system comprises an air supply unit (ASU), a gasifier unit, an SOFC, a G/T, a heat recovery steam generator, and an S/T. The system configuration of the gasifier unit, the heat recovery steam generator, and the steam turbine system is an assumption model by authors. To operate the system as shown in Fig. 3 using a minimum load factor of 65%, the efficiency in each device is reduced. The ASU is a system configuration supposing the internal compression type air separation unit integrated with liquefying process [17]. The quantity of air supplied from a blower $BW_{asu,air}$ in the ASU changes with the load factor in the system. Furthermore, the power consumption $CP_{asu,air1}$ of a compressor changes with the magnitude of load. Moreover, based on the load factor of the system, powdered coal is supplied to the gasifier with the nitrogen produced in the ASU. Because raw syngas from the gasifier contains impurities and greenhouse gases, it is necessary to introduce processes that eliminate or reduce these undesired substances. As a result, hydrogen containing only trace amounts of impurities can be supplied to the SOFC.

Although high-temperature compressed air is supplied to the SOFC by the air compressor $CP_{gt,air}$, the operating temperature of the SOFC changes because the air temperature of the $CP_{gt,air}$ decreases when the load factor of the proposed system reduces. Therefore, when the load factor, rather than the rating, of the proposed system reduces, the power generation efficiency of the SOFC decreases. Moreover, as the calorie supply to the G/T reduces, the overall efficiency of the G/T reduces. As a result, the exhaust heat from the G/T is supplied to a heat recovery steam generator, and the output of the S/T changes.

2.2. Output model for the IGFC

2.2.1. ASU

High-purity heat integrated air separation column is assumed in this study two columns are installed in ASU, HPC is high-pressure column and LPC is low-pressure column. The air is compressed to about 0.580 MPa by the compressor $CP_{asu,air}$ and as a result its temperature increases to about 101 K. The pressure of LPC expands to 0.1157 MPa by a compressor. ORLA and ORVA in Fig. 3 are oxygen-rich liquid air and oxygen-rich vapor air, respectively. Moreover, OP, LLNP, and NP are oxygen product, low-purity liquid nitrogen product, and nitrogen product.

Fig. 4 shows the equilibrium state between the air liquefaction