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Electric power control of a power generator using dissociation expansion of a gas hydrate

Shin'ya Obara[a,*], Daisuke Mikawa[b]

[a] Power Engineering Lab., Applied Energy Course, Factory of Engineering, School of Earth, Energy and Environment Engineering, Kitami Institute of Technology, Koen-cho 165, Kitami, Hokkaido 090-8507, Japan
[b] Hokkaido Electric Power Co., Inc., Oodori Higashi 1-2, Chyou-ku, Sapporo, Hokkaido 060-8677, Japan

HIGHLIGHTS

- Power control of gas hydrate power-generation system was described.
- Relation between power factor of load and power quality was clarified.
- Power stabilization by combined cycle power generation using gas cogeneration.
- The proposal for single-family houses by adjustment of inertia system.

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ABSTRACT

The unique dissociation expansion characteristics of gas hydrates allow a large pressure difference to be obtained from a small change in temperature. This suggests that a clean actuator system may be built that can use low temperature heat from the nighttime air and high temperature heat from daytime solar radiation or other sources. This study proposed a generator that could operate using a small temperature difference, by leveraging the change of state of a gas hydrate. The dynamic characteristics of an alternating current power supply from a gas-hydrate power-generation system (GHGS) have not previously been reported. The objective of the study was to achieve an electric power supply of acceptable quality (frequency and voltage) from a GHGS while tracking demand. A pressure regulating valve under P-I control was used to adjust the supply of high-pressure dissociated gas to the actuator. As the GHGS was of the batch type, a hybrid system including a conventional gas-powered generator was also investigated. A numerical analysis showed that, when a flywheel with an inertia constant of 6.9 kg/m^2 was installed, the hybrid system was able to provide a stable electricity supply for an individual house.

1. Introduction

In cold regions, large amounts of fossil fuels need to be burned in order to meet the heating demands, producing significant discharge of greenhouse gases. This study investigated a generation system using a gas-hydrate heat cycle. In the phase transition of gas hydrate, a small difference in temperature produces a large difference in pressure. For example, when using CO_2 hydrate, a pressure difference of 3 MPa is obtained from a change of approximately 10 K. This suggests that a clean actuator system may be built that can use low temperature heat from the nighttime air and high temperature heat from daytime solar radiation or other sources. The proposal system is a new electric power system generated by renewable energy and unutilized energy. Previous studies using the change in state of gas hydrates include an experimental investigation of cold energy storage using gas hydrates by Xie et al. [1] and the use of entropy for low temperature energy generation by Bi et al. [2]. Regarding the latest fundamental examination regarding CO_2 hydrate, the kinetics in porous media by Yang et al. [3], semiclathrate hydrate process for pre-combustion capture of CO_2 by Zheng et al. [4], Raman spectroscopic of carbon dioxide separation by Cai et al. [5] and dissociation characteristics of CO_2 hydrate with THF by Sun et al. [6], etc. have been reported. Ohfuka is analyzing low-temperature driven power generationused a heat engine by clathrate hydrate [7].

This study investigated the control of a gas-hydrate power-generation system (GHGS). Obara et al. investigated the generation performance of a compressed gas engine using the dissociation expansion characteristics of a gas-hydrate and proton-exchange membrane fuel

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[*] Corresponding author.
E-mail address: obara@mail.kitami-it.ac.jp (S. Obara).

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Nomenclature

E, $\dot{E}$	voltage [V] (“·” is a vector representation)
$\dot{E}_0$	no-load induced electromotive force [V]
f	frequency [Hz]
Δf	frequency deviation [Hz]
gas	kind of the gas
ΔH	reaction heat of formation and dissociation of gas-hydrate [kJ/kg]
I, $\dot{I}$	current [A]
$\dot{I}_{ar}$	armature current [A]
$\dot{I}_d$	d component of current [A] (Fig. 9 (b))
$\dot{I}_q$	q component of current [A] (Fig. 9(b))
J	moment of inertia [kg·m^2]
j	imaginary unit
K	gain
L	latent heat [J/g]
Δl	deviation of load [W]
l_e	output of electric power [W]
l_g	output of high-pressure gas engine [W]
Δl	power load [W]
Δl_d	power demand [W]
m	mass [kg]
m'	mass flow rate [kg/s]
P	electric power [W]
P_f	power factor
p	pressure [MPa]
Δp	difference pressure [MPa]
Q	quantity of heat [kW]
r	radius [m]
r_a	resistance of armature coil [Ω]
S	hydration numbers
$signal$	control signal
t	sampling time [s]
T_e	electric torque [N·m]
T_g	machine torque of the high-pressure gas engine [N·m]
T_m	output torque [N·m]
TC	time constant
TV	temperature [K]
V	volume [m^3]
x_a	armature-reaction reactance [H]
x_{ad}	reactance component of the same direction as magnetic field electromotive force [H] (Eq. (7))
x_{aq}	reactance component which intersects perpendicularly with a magnetic field electromotive force [H] (Eq. (8))
x_d	vertical-axis synchronous reactance [H] (Fig. 9(b))
x_l	leakage reactance [H]
x_q	horizontal-axis synchronous reactance [H]

Greek characters

β, θ, δ	power factor angle [rad]
ω	number of revolutions [rad/s]

Subscript

a	actuator
bt	buffer tank
c	heat medium
d	dissociation
dp	damping
e	electricity
ex	exciter
f	flywheel
g	high-pressure gas engine
gh	gas-hydrate
lf	low pass filter
mf	magnetic field system
p	pump
Δp	differential pressure [MPa]
r	reactor
rat	rated
ref	reference value
rg	regulator
set	set value
$signal$	control signal
$stab$	stabilization signal
t	sampling time
t_0	initial condition
v	pressure regulating valve
w	water

cell [8] and clarified the fundamental physical properties of a GHGS using CO_2 hydrate. A distributed energy system using a GHGS was previously investigated [9]; moreover, the operational planning of a GHGS was also clarified [10]. In addition, high-pressure gas storage and the use of CO_2 gas hydrate as a battery were previously investigated [11], and the development of an energy system combining storage with natural-gas cogeneration and a GHGS was reported. However, the dynamic characteristics of a GHGS under fluctuating loads have not yet been clarified, and a control method for ensuring the quality of the power output of a GHGS has yet to be investigated. No existing study has reported the quality of the alternating current output of a GHGS. The flow of dissociated gas from the hydrate is supplied to an actuator by a pressure regulating valve, allowing the output of alternating current from the GHGS to be controlled. This paper presents an output model for a GHGS, with the goal of stabilizing the supply of electric power by Proportional-Integral (P-I) control of the pressure regulating valve. If development of the proposal system is successful, stable electricity is obtained from unstable renewable energy.

Because the GHGS alternates power generation by gas dissociation with energy storage by hydrate formation, long-term uninterrupted running is challenging. The quality of alternating current from a standalone hybrid system for individual houses connected to a gas-powered generator was investigated. This hybrid system exhibited a GHGS-rated power of 750 W and the system-rated power of 4.5 kW. Because household power loads fluctuate significantly, achieving load following by the proposed system was challenging. A second objective of the study was therefore the stabilization of the output of the hybrid system in individual houses. To achieve this, an inertial flywheel system was connected to the gas-powered generator. This allowed the supply from the hybrid system to an individual house to be controlled.

2. GHGS

2.1. Formation and dissociation of gas hydrate

With the change in temperature and pressure, a molecule of water can transform into an ice-like solid by combining with a gas molecule. Fig. 1 shows a schematic of a gas hydrate. When the gas molecule is combined with the water molecule, this is called formation, and when it is discharged, this is called dissociation of the gas hydrate. Eq. (1) gives the stoichiometric equation for the formation and dissociation of a gas hydrate. Here, *Gas* and H_2O represent the gas and water molecules, S is the degree of hydration, and ΔH is the reaction heat. In the case of CO_2 hydrate, 1 g of water contains 216 ml of CO_2 gas under standard