DEVELOPMENT AND EVALUATION OF MICROGRIDS ISLANDED OPERATION METHOD WITH DEMAND SIDE CONTROL

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Abstract – The microgrid has the values of the energy security improvement by islanded operation in addition to the energy saving effect by the energy trading. When the microgrid is operated under islanded condition, several problems about stability and power quality may occur. We built the small scale microgrid verification test facility in the Yokohama Research Institute, and carried out verification test of islanded operation.

In this paper, we show a new islanded operation method of microgrid that composed with only one islanded driving-compliant gas engine and various distributed generators of no-rotating type, and results of verification test using this control method. The proposed method is to use a demand side control, parallel control of controllable distributed generators and state of charge control for battery.

Keywords: Microgrid, Holonic Energy System, Islanded Operation, Verification Test, Distributed Generation, Demand Side Control

1 INTRODUCTION

In Japan, diffusion of renewable energies(REs) for the achievement of the CO₂ reduction targets by Kyoto Protocol and efficient utilization of energy is expected. However, it is concerned that the fluctuating power of REs might degrade power quality such as voltage and frequency of the utility power grid. A microgrid which compensate fluctuation of REs within a specific area using controllable equipments such as gas engine combined heat and power(GE-CHP) or battery is proposed to increase REs without degradation of utility power.[1]

Under this social circumstance, we propose the Holonic Energy Systems(HES).[2] “Holonic” is derived from Greece term “Holon” that is combination of “Holos” meaning the whole and “On” meaning parts, that is to say, express a good balance between the whole and its parts. The HES is the system that distributed generation and centralized power generation are organically combined to establish optimal operation. The HES can solve the conflicting issues such as stable supply of energy, environmental concern and economic efficiency by organically harmonizing while making the best use of each feature of distributed power systems and the utility power grid. The HES has the following values:[3]

i ) Enhanced energy security in case of utility power grid failures or disasters.

ii ) Enhanced energy efficiency and CO₂ mitigation by networking distributed energy resources.

iii ) Support to the power grid by demand and supply adjustment and voltage control.

In particular, when utility power grid is blacked out due to system trouble or disaster, the electric power and heat can be supplied by microgrid islanded operation that uses distributed generators(DGs). Therefore, in facilities that have important equipments such as communication system and in local disaster control center, there are high needs of stable supply of energy.

A thermostatic ratio of power generations side is not always consistent with that of demand when microgrid is planned with a major focus on CHP. Therefore, the capacity of the generators in microgrid often decreases to bellow total loads from perspective of effective utilization of exhaust heat. Moreover, The islanded operation function is not necessarily installed for all existing small GE-CHPs which are used on microgrid. But it costs to make all DGs correspond to islanded operation. Thus, there are the following issues especially on islanded operation of microgrid by using small GE-CHPs;

- Assurance of system voltage and frequency under load fluctuation and RE fluctuation.[4]
- Selection of prioritized loads within the range of generator capacity, excluding capacity of intermittent RE.
- Battery management on the state of charge(SOC) which is necessary for suppressing fluctuation during long islanded operation.
- Control which is necessary for parallel operation of a few islanded driving-compliant GE and other DGs.

For the achievement of stable islanded operation of microgrid for a long term, it is thought that on-off control of loads according to RE fluctuation, increase of load following speed of CHP, and operation of CHP related to SOC of battery are effective. Integrated control of the distributed generators even with the load side control have not been examined before.

This paper presents an islanded operation method of microgrid which aims at stable and efficient use of regional energy system. We established integrated control method for plural and many kind of generators(GE-CHP×3, photovoltaic power generation system(PV), wind turbine(WT)×2, power conversion system(PCS))
such as blackout start sequence, loads control by demand side controller according to PV and WT power fluctuation, battery control to maintain SOC within the constant range and parallel control of GE. This method aims at frequency within 50±0.2Hz and voltage within 202±20V(or 101±6V) during continuous operation over 24hours.

2 MICROGRID ARCHITECTURE

Tokyo Gas Co. had constructed a microgrid verification test facility in the Yokohama Research Institute as shown in Figure 1. This microgrid composed with an islanded driving-compliant GE-CHP(GE2), non-islanded driving-compliant GE-CHPs(GE1, GE3), PV, WT, lead-acid battery, nickel hydride battery, PCS, uninterruptible power system(UPS), and demand side controller. All DGs including GE-CHPs are utility interconnection by the inverter. Moreover, this microgrid devides the load according to the electric power quality. The high quality loads(Loads B) using by UPS are loads of a possible power supply when blackout of utility power grid. The load of this premium power supposes server and medical equipment that even voltage sag is not permitted. The middle quality loads(Loads A and Loads C) is bloken down once when blackout of utility power grid, but it can supply power after a few seconds to few minutes by starting GE2 and other DGs. The load of this quality is assumed lights, air conditioners and general household appliance. This microgrid connected lights, air conditioners, artificial load, electric heat pump(EHP), heater, and elevator which is driven by an induction motor.

3 CONTROL METHOD

3.1 Demand side control

The load more than the capacity of the controllable DGs such as GE-CHP can not be connected in islanded operation mode. Thus, it controls to which the amount GE-CHP squeezes the output when the amount of power generation in the RE power supply is large, and there is the issue that cannot utilize generation power of REs power supply effectively. Figure 2 shows the result of the parallel islanded operation of GE2 and PV[5]. We are proposing the control technique that is called a Demand Side Control(DSC) for this issue solution. The DSC is on-off control of the specific load according to the power supply and demand situation in the microgrid that changes hourly by the REs fluctuation and load fluctuation. Figure 3 shows DSC sequence. It sets priorities to the specific load of the DSC, and it control application and interruption of the load according to it. The kind of the specific load is equipment for the comfort such as the air conditioner, some light and home electronics. In this microgrid, 5 loads to consist of heater and EHP(total 15kW) are targeted in DSC. L1 to L3 are heaters. L4 and L5 are EHPs. The priority level of Li is higher than that of Li+1.
3.2 Transition sequence to Islanded operation

Each DGs that composes this microgrid stops generation when the utility grid is blacked out, because it is required by the utility interconnection guideline by inverter. Then, GE2 that corresponds to blackout start changes to islanded operation mode, and the voltage of microgrid is established. In this microgrid system, there are two 100kVA transformers and PCS that has capacitor. Thus, if the voltage is rapidly raised, there is a possibility that the current that exceeds acceptable amount of the GE-CHP’s inverter flows because of these excitation. To avoid that prospect, the voltage is gradually raised spending the time of about 30 seconds by a soft start of GE2.

After establishing the voltage of microgrid, other DGs can start in a usual utility interconnection mode. The electric power characteristic when GE start is shown in Figure 4. This characteristic is start-up of cell-motor for the engine start. When, the maximum power consumption is about 10kW. Thus, the power supply is limited until GE1 and GE3 start.

The PCS has such the feature as the power can be interactively input/output and the output response is high speed. Therefore, the power supply restart was decided in the order of PCS, GE3, GE1, PV, and WT.

![Figure 4: Power characteristic on GE start-up.](image)

3.3 Gas engines and PCS Parallel control

GE2 which supplies voltage in islanded operation mode has stable voltage and frequency compared with rotating type GE. On the other hand, GE2 has a fault that inertial force and current overload capacity are small. Therefore, it is weak to rapid fluctuation of load and RE power supply. Figure 5 shows the acceptable amount of load input and interruption of GE2. When the load input and interruption amount exceed the allowable amount, the microgrid blacks out again because the microgrid loses voltage supply by cutoff of inverter. Thus, a stable islanded operation is difficult when RE power supply interconnect and the load using induction motor in an elevator connects.

However, if it can compensate for the load fluctuation and RE fluctuation by other DGs, the gate block of the GE2 inverter can be prevented and operates stably. In particular, the method that the output of GE2 keeps by the output adjustment of GE1, GE3 and PCS within the constant range is devised. As for the output target of GE2, about 10-12kW is the most stable in both the load input and interruption.

![Figure 5: Allowable value of load input and interruption.](image)

GE2 controls voltage in islanded operation mode. First, the output of GE2 varies depending on load and RE fluctuation. Then, it keep GE2 output target value by follow-up of three DGs. The risk of the black out again by gateblock of inverter can be decreased by this control. Figure 6 shows control block diagram of constant output control of GE2 by parallel control of GE1, GE3 and PCS. Each DG’s controllers are PID controller. PCS output command by PCS controller is decided from the difference between GE2 output power and reference power(12kW), GE3 output command is decided from the PCS output and battery SOC. If the battery SOC decreases, GE3 output command increase for battery charge. And, GE1 output command is decided from the PCS output and the difference between GE3 output and reference power. The charge and discharge speed of the battery is very fast than the gas engines. In this test facility’s battery, time from 0kW to 50kW is less than 0.2 seconds. That is, the PCS compensates for the fluctuation in electric power that the gas engines cannot track. Figure 7 shows each DGs output behavior by parallel control method. For the step-shaped load fluctuation, at first PCS follows it, and GE3 follows it to return the output of PCS to 0 successively. Furthermore, it is the behavior that GE1 follows so that PCS and the GE3 output return to a reference value.

![Figure 6: Parallel controller.](image)
3.4 Battery SOC management control

In the long islanded operation, neither the amount of total charge nor the amount of total discharge of battery is necessarily corresponding. Thus, SOC may become 100% or 0% sometime. When SOC becomes 100%, the output control in the direction of the charge becomes impossible. Oppositely, when SOC becomes 0%, the output control in the direction of the discharge becomes impossible. The SOC of the storage battery in islanded operation of microgrid shows in Figure 8. In this case, total amount of discharge are more than total amount of charge, and SOC keeps decreasing. Like this risk can be reduced that if the capacity of the storage battery increase, but it is not realistic from the respect of the cost and the installation space. Then, to enable islanded operation continued with the storage battery of small capacity, we built the SOC Management Control that operated SOC within the constant range[6][7].

![Figure 7](image)

**Figure 7:** Each generators behavior by Parallel control.

![Figure 8](image)

**Figure 8:** Change of SOC in battery operation.

In this control, SOC controls controllable DGs where the output can be adjusted excluding PCS. In particular, SOC controls PI control based on the deflection between the SOC value and the reference value so that SOC should not deviate from 70±5%. And, charge and discharge at the speed that there is no obstacle in the stabilized operation up to the return to the reference value by feeding back PI control output to the output instruction value of GE3. Moreover, GE1 and GE3 output approaches ratings, and there is a possibility that the output adjustment reserve strength for the charge decreases in daytime. Therefore, when SOC becomes 65% or less, the output target value of GE2 adjusts for SOC control. Figure 9 shows the block diagram of the SOC management control.

![Figure 9](image)

**Figure 9:** SOC Management Controller.

In this verification test, the battery used nickel hydride battery which was superior in the charge and discharge efficiency characteristic, high discharge rate characteristic and high speed charge and discharge characteristic. The change of SOC may become extremely small because the actual battery is large capacity at 127kWh in this test facility. Then, the capacity of the storage battery assumed 10kWh from the respect of the effect confirmation of SOC management control.

3.5 Integrated control model

Figure 10 shows the integrated control model that combines these three control logic. Only GE2 is controlled the output based on bus voltage of microgrid, and other DGs is controlled the output based on the active power output of GE2 and parallel controller.

![Figure 10](image)

**Figure 10:** Integrated control model.
RESULT OF VERIFICATION TEST

4.1 Transition to islanded operation after blackout

The blackout of utility power grid was imitated by opening the breaker of microgrid connection point to the utility power grid. When blacking out, all GEs were the halt conditions. Figure 11 shows the behavior of loads and DGs of the shift from the blackout to the islanded operation.

![Figure 11: Transition to islanded operation.](image)

In the high quality loads (Loads B), the supply capability instantaneously changed into the power by the battery after blackout, and kept power supply. GE2 started at about 2 seconds after blacked out, the voltage raised gradually by a soft start, and the voltage built up at about 40 seconds after blacked out. UPS interconnected again after voltage establishment, and PCS started successively, and PV and WT interconnected system last.

The time to interconnection and starting power output of DGs is shown in Table 1. It suggests that DGs expect for PV and WT started and the power was supplied within 2 minutes after blacked out. This is a result of blackout with all GE stopped. When electricity go out with GE driven, time until restarting power supply will be shortened further. Moreover, it was understood that the output of GE2 that was the voltage supply maintains the target value by the output control of PCS, GE1 and GE3.

<table>
<thead>
<tr>
<th>DG variety</th>
<th>Time to start-up [sec]</th>
<th>Time to power output [sec]</th>
</tr>
</thead>
<tbody>
<tr>
<td>UPS</td>
<td>5</td>
<td>—</td>
</tr>
<tr>
<td>PCS</td>
<td>51</td>
<td>56</td>
</tr>
<tr>
<td>GE3</td>
<td>68</td>
<td>107</td>
</tr>
<tr>
<td>GE1</td>
<td>74</td>
<td>117</td>
</tr>
<tr>
<td>PV</td>
<td>205</td>
<td>205</td>
</tr>
<tr>
<td>WT</td>
<td>351</td>
<td>351</td>
</tr>
</tbody>
</table>

Table 1: Time to start-up and power output of DGs.

4.2 Evaluation of power quality and stability

Figure 12 shows the result of long term islanded operation during a day. The verification test chose the day when the output of the PV fluctuated severely. Moreover, this is data of 6 hours from the morning to daytime that is the most difficult condition in a day for the islanded operation. From this result, GE2 followed it for load fluctuation by elevator running and PV fluctuation momentarily, but GE2 returned to the targeted value by the output change of other DGs. A stable islanded operation was observed. The load began to increase from about 7:00 gradually, and reach 50kW around 8:30. Therefore, though output of GE1 and GE3 became saturated and these generators could not follow in the direction of the output increase, the battery worked to compensate imbalance. At this time, though SOC decreases because the amount of discharge increases, SOC increases by raising the output target value of GE2. SOC kept 70% at time zone when the GE output was not saturated.

The frequency and voltage has been hardly affected by the load fluctuation and PV fluctuation. Table 2 shows the maximum value, the minimum value and allowable value of the voltage and frequency in the islanded operation during a day. The target range is the same as that of the electric power company in Japan. The frequency and voltage of 3ϕ 200V and 1ϕ 100V system did not deviate from the target range through a day.

In this verification test, we achieved long term stable islanded operation that might not be blacked out again while the electric power quality was maintained at the utility grid level.

4.3 Evaluation of Demand Side Control

Figure 13 shows PV power, on-off state of specific loads and the amount of load of Loads A. When the PV power increased, the number of “on” state loads increased. On the contrary, when the PV power decreased, the number of “off” state loads increased. Thus, the generation power of PV that is a non firm power supply is suitable for the equipment such as heaters and EHP effectively in an islanded operation. Similarly, all of the DSC specific loads showed turning “on” in a light load time zone such as nighttime because there was margin of DGs’output.
Table 2: Result of power quality in islanded operation.

<table>
<thead>
<tr>
<th></th>
<th>Minimum value</th>
<th>Maximum value</th>
<th>Target range</th>
</tr>
</thead>
<tbody>
<tr>
<td>3φ200V [V]</td>
<td>193.5</td>
<td>201.7</td>
<td>182 – 222</td>
</tr>
<tr>
<td>1φ100/200V [V]</td>
<td>95.1</td>
<td>102.6</td>
<td>95 – 107</td>
</tr>
<tr>
<td>Frequency [Hz]</td>
<td>49.96</td>
<td>50.03</td>
<td>49.80 – 50.20</td>
</tr>
</tbody>
</table>

NOTE: Load state “i” is number of ON state Load.

Figure 12: Result of islanded operation.

Figure 13: Result of Demand Side Control.
5 CONCLUSIONS

We developed the islanded operation method for stability and high power quality using one islanded driving-compliant GE-CHP and various DGs. Then, we demonstrated islanded operation with this control method, and we achieved the following results:

1) All DGs could be started and interconnected by one islanded driving-compliant GE-CHP, and to transition to the islanded operation of microgrid.
2) The power supply to certain loads could be restarted within 40 seconds after blacked out. And the power supply to other loads was able to be restarted within 2 minutes.
3) The electric power quality maintained utility grid level by parallel control of PCS and GE-CHPs when operated islanding from the utility power grid.
4) Battery SOC was able to be operated by the SOC management control within the range of 70 ±5%.
5) DSC controllable loads such as heaters were able to be utilized completely by DSC when the amount of PV power generation was sufficient or the loads were light.
6) A long time stable islanded operation was achieved by the proposed integrated control method.

Therefore, the effectiveness of islanded operation method developed by this research was confirmed.

6 REFERENCES


7 APPENDIX

A list of abbreviations.
RE : renewable energy
GE-CHP : gas engine combined heat and power
HES : Holonic Energy System
DG : distributed generator
SOC : state of charge
PV : photovoltaic power generation system
WT : wind turbine
PCS : power conversion system
UPS : uninterruptible power system
EHP : electric heat pump
DSC : demand side control
INV : inverter