Electricity Cluster-Oriented Network: A Grid-independent and Autonomous Aggregation of Micro-grids

Kaoru Koyanagi Yusuke Hida Ryuichi Yokoyama
Graduate School of Environment and Energy Engineering
Waseda University
Tokyo, Japan

Satoshi Nagata
VPEC Inc.
Tokyo, Japan

Kunihiro Nakao Tomoyuki Hirai
Engineering Department
Osaka Gas Co., Ltd.
Osaka, Japan

Abstract— A new type of micro-grid called "Electricity Cluster-oriented Network" is proposed. The proposed Electricity Cluster-Oriented Network is the aggregation of the loosely-coupled, autonomous and independent local network called "cluster", and the expansion in the scale is easily achieved as the additional power demand arises. This approach will be possible to hold down initial investment. Mathematical models of the Electricity Cluster-Oriented Network for computer simulations were developed by MATLAB/Simulink, and the dynamic properties to maintain frequency and voltages in the cluster are presented. In addition to the computer simulations, experiments using small-sized laboratory equipment were carried out to show that it works as might have been expected.

Keywords-Distributed Generation; Micro-grid; Battery Energy Storage; Renewable Energy; Smart grid

I. INTRODUCTION

Renewable energies such as wind power and solar power resources are valuable energy resources which can contribute to improvement of self-sufficiency rate of energy and can be used to reverse global warming. However, when there is a large amount of penetration of renewable energy generations into a grid, some problems will arise in the present distribution power network, due to instability of power output and large reverse power flow caused by the renewable energy generation.

In study of recent new electricity supply system there is a way of thinking of local production for local consumption by the so-called micro-grid which supplies the area demand by the area electric power resources, and several demonstrations have been performed also in Japan.

From the viewpoint of local production for local consumption of electric power energy, the authors proposed and studied the possibility of a new type of micro-grid to meet regional expansion of the area's electricity demand and supply by the addition of electricity-cluster. It is called here, the Electricity Cluster-Oriented Network.

The proposed Electricity Cluster-Oriented Network is the aggregation of the loosely-coupled, autonomous and independent local network called "cluster", and the expansion in the scale is easily achieved as the additional power demand arises. This approach will be possible to hold down initial investment.

The authors developed dynamic models of renewable energy generators and battery energy storage system by MATLAB/Simulink, performed computer simulations to investigate the fundamental capabilities, In addition to the computer simulations, experiments using small-sized laboratory equipment were carried out to show that it works as might have been expected.

This paper presents a proposal of cluster-oriented network and shows results of the feasibility study to evaluate its technical possibility.

II. ELECTRICITY CLUSTER-ORIENTED NETWORK

The feature of the proposed "Electricity Cluster-oriented Network" compared with the other grids is indicated in the Table 1. Key points are stated as follows.

- Electric power is produced locally for local power consumption, mainly by renewable energies
- Battery energy storage system (BESS) plays a dominant role in stable electric power supply in each cluster
- Expansion of scale is done by addition of electricity clusters which are coupled with DC interconnection, and the aggregation of clusters improves power supply reliability of a whole system
- Grid-independent and autonomous operation is intended for applications in remote area or developing countries

The feature of the proposed cluster-oriented network is supplemented below.

Table 1 Feature of Electricity Cluster-Oriented Network compared with the other grids

Items	Conventional Grid	Micro-grid	Electricity Cluster-oriented Network
Power Sources	Large-scale Fossil-fired, Hydro and Nuclear	Small-sized GE, FC, PV and Wind, etc. (Anchored by Controllable Generations)	Renewable Energy such as PV, Wind and Micro-hydro, as well as GE, FC, etc.
Energy Storage	Pumped storage Hydro	Battery Energy Storage System (BESS) is crucial for the system	
		BESS is cooperative in the operation with the other generations	BESS plays a dominant role for stable power supply supported by the other generations
Inter-connection	Between utilities	Normally interconnected with utility , but independent operation in emergency	Normally independent operation
Power Transfer	Between utilities	No power transfers between Micro-grids	Power transfer between loosely-connected clusters
AC/DC	AC	AC	AC (DC in future)
Scale	Large	Medium	Small
Scalability	Poor（Long-rage Planning）	Good（Short-range Planning）	Excellent（Scaled up autonomously depending on the needs）
Applications	Large-scale social infrastructure	Distributed network for next generation（High energy efficiency by CHP）	For massive development of RES, developing countries without IT infrastructure, un-electrified areas, islands, etc

1) The BESS acts as a stable supply source of electric power, and not as a compensation of difference in demand and supply. (See Fig. 1) In compensation of difference in demand and supply, kW (electric power) is a control target. However, when BESS is regarded as the supply resource, kWh (the energy) is more important in the control rather than kW.

2) The interconnection between clusters is the DC link via battery. Therefore, when it is necessary, different rated frequency is allowable in each cluster. Thus, supply of electric power for different quality as well as DC distribution is also considered as future development.

III. STABILITY OF THE NETWORK AND THE METHOD OF INTERCONNECTION BETWEEN CLUSTERS

A. Control of Frequency and Voltages in a Cluster

As for voltage (reactive power) control by generators, droop control according to each reactive supply capability of the generator is employed like the case of conventional micro-grid[3][4]. Fig.2 shows reactive power control by voltage-source inverter. In addition, reactive supply sources such as SVC will be needed depending on the structure of the network.

Fig.3 shows an example of single cluster. The generators in the cluster are all types of generation, renewable resources and controllable generators(gas co-generation, fuel cell, biomass generation, etc.). As for frequency control, when there are no synchronous generators with the rotating inertia like conventional grid and only the inverter-interfaced generations are operated, the following control method is proposed.

- Frequency in a cluster is determined by an inverter implemented in the BESS.
- The inverter is operated under control mode of constant voltage and constant frequency (CVCF) (See Table 2).

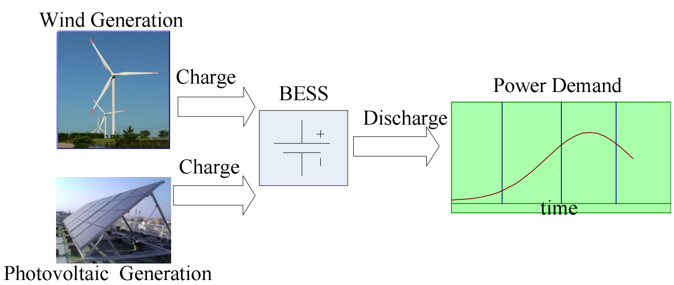


Fig. 1 Role of BESS in the cluster

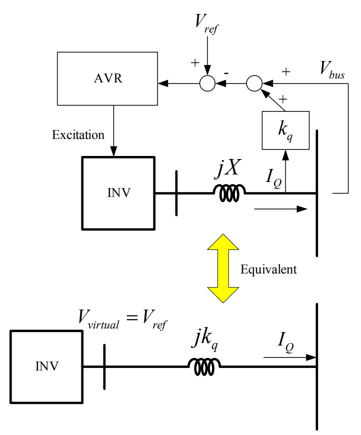


Fig. 2 Reactive power control by voltage-source inverter

B. *Interconnection between Clusters*

When expanding the scale due to increase of electricity demand, there is a choice of expansion by addition of clusters as well as expansion inside the single cluster.

By leveling charged energy (State Of Charge, SOC) in the BESS among the whole clusters, expanding by addition of clusters has the capability of avoiding the lack of supply, in advance, which may occur in the specific cluster, and then, contributing to improvement of the power supply reliability.

An additional inverter for interconnection between clusters is installed in BESS as shown in Fig. 4 and tie-line power is controlled by the inverter. APR control listed on Table 2 is employed as the control of the inverter.

A way of thinking for control of the tie-line power is described below.

- The control of the tie-line power, that is, direction and amount of power flow, is performed by the inverter dedicated for interconnection which is implemented in BESS (APR mode).
- It is controlled so that the tie-line power may flow from the cluster with a lot of SOC of BESS to another cluster with a little SOC. This is the same analogy as transfer of synchronous energy between the synchronous generators in conventional grids.
- To achieve this scheme, it is necessary to measure the charged energy of batteries (SOC) of cluster A and B with high accuracy to control the inverter.
- The amount of charged energy of battery (SOC) is reflected in the frequency of the voltage wave produced by the main inverter(CVCF mode). That is, in a case with a lot of the charged energy, the frequency of the cluster is maintained rather high within the allowable range, and in a case with little charged energy conversely, the frequency of the

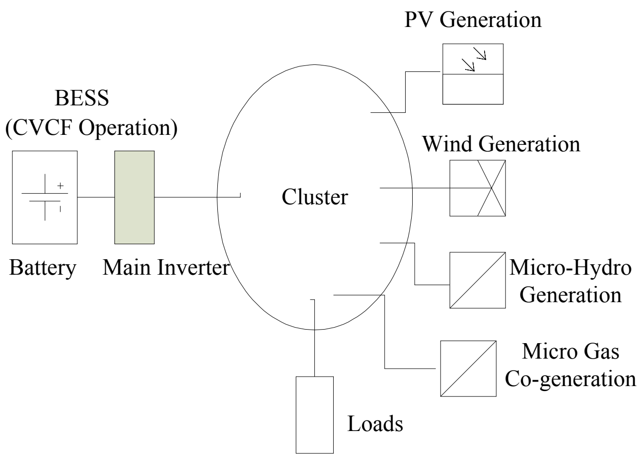


Fig. 3 An example of single cluster

Table 2 Control scheme of inverter for BESS

Control Mode	Application	Control
APR	Grid-dependent	Active Power (P) and Reactive Power (Q)
CVCF	Grid-independent	Voltage(V) and Frequency(f)

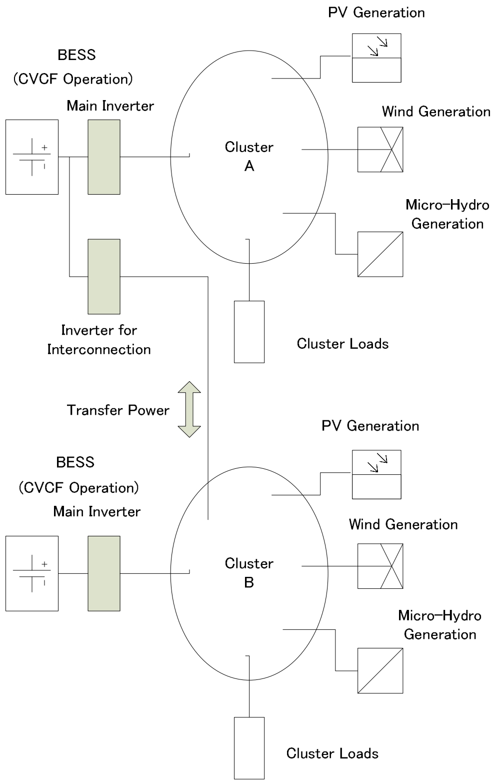


Fig. 4 Interconnection between Cluster A and B

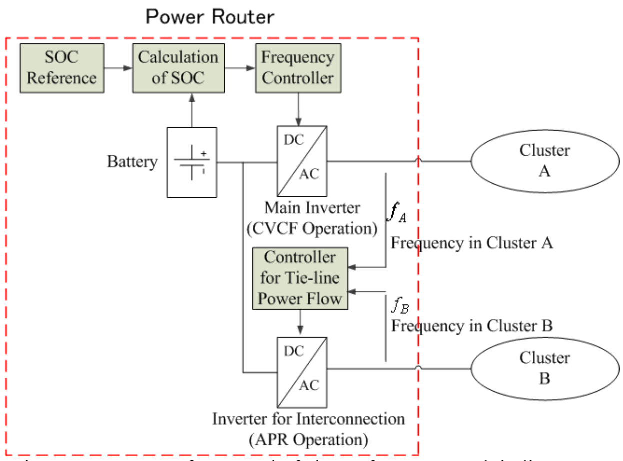


Fig.5 Power Router for control of cluster frequency and tie-line power flow

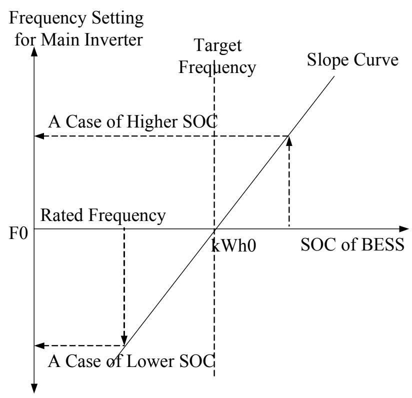


Fig.6 An example of frequency setting for main inverter with SOC

cluster is maintained low.

- When doing this, frequencies in cluster A and B are detected and compared to control the inverter dedicated for interconnection, and it is decided to flow power into a cluster of low-frequency from a cluster of high-frequency. Frequency is a global electrical signal in AC system, and then, tie-line power control is performed only by detecting local frequency without any special communication lines.
- The other merit of changing frequency of the cluster within the specified allowable range is to help controllable generators such as gas-cogeneration, fuel cell, etc. to control their power outputs. This will realize AFC function based on locally-detected frequency without any special communication.

Fig.5 shows control scheme of cluster frequencies and tie-line power between clusters. The box enclosed by red dotted line in Fig.5 is specific apparatus for the proposed Electricity Cluster-oriented Network, and is called here, "Power Router". The Power Router has functions of management of energy storage and interconnection between adjacent clusters, and is elemental technology in the proposed network.

Further, without limit to the specific form, the interconnection among clusters can be flexibly composed of the radial construction or the cascade construction.

IV. SIMULATION STUDIES USING CLUSTER MODEL DEVELOPED BY MATLAB/SIMULINK

Simulation studies were carried out in order to demonstrate the effect of interconnection between clusters by proposed Power Router.

A. Simulation Conditions

As renewable energy generation, photovoltaic generation and wind power generation (direct AC-link system) were considered. Both cluster 1 and 2 are same in composition. The outline of cluster components is listed on Table 3.

The following two cases were simulated for comparison.

1) Case without the interconnection between two clusters

This is the case that cluster 1 and 2 are operated independently. The change of demand curve in cluster 1 is larger, and smaller battery energy storage capacity is assumed than cluster 2, so stable control of supply and demand is more difficult than cluster 2.

2) Case with the interconnection between two clusters

Both the frequencies and the charged energy in BESS(SOC) in two clusters are expected to be level with power transfer between clusters controlled by inverters dedicated for cluster-interconnection.

B. Simulation Results

The followings were found from the simulation results.

- In both the cases with and without interconnection by electrical power router between clusters, frequency and voltage can be kept stable.
- Without interconnection, the frequency falls a lot more for cluster 1 than cluster 2 because there is a lot of battery discharged capacity, and this yields more reduction of SOC in Cluster 1.
- The leveling of both frequencies and battery charged energies (SOC) in two clusters were achieved in the case with interconnection between clusters by electric power router, and the validity of the proposed control method for power flow between clusters was demonstrated. Fig.7(a) and (b) shows changes of SOC in Cluster 1 and Cluster 2.
- The leveling effect is seen in frequency curves in two interconnected clusters. On the other hand, there are no changes in voltages between the two cases. This is because the electric power router applied in this study controls only active power flow and the power factor of power flow is kept at unity (reactive power is zero) by the electric power router.

Table 3 Outline of Cluster Components

Cluster	Generations	BESS	Inverter for Interconnection
1	Photovoltaic Gen. 33kW Wind Gen. 30kVA	100kW, 6.7kWh Frequency control: 0.3(Hz)/40%SOC	<u>Power capacity</u>: 100kVA <u>PID Controller</u> Gain: 667 (pukW/puHz) Time Constant: 10 second
2	ditto	300kW, 50kWh Frequency control: ditto	

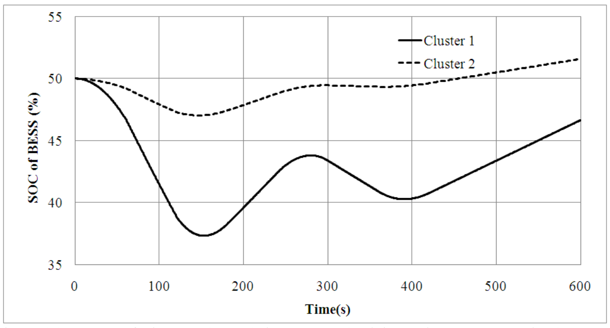


Fig. 7(a) State of charge (SOC) in BESS (Without interconnection)

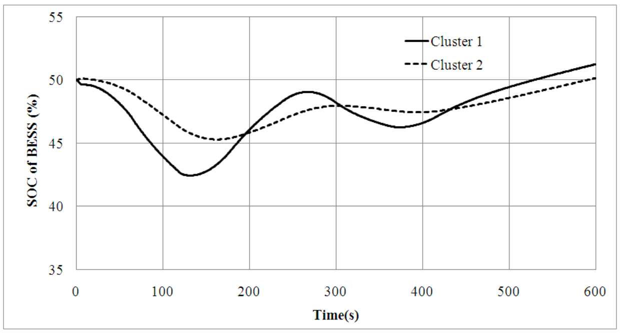


Fig. 7(b) State of charge (SOC) in BESS (With interconnection)

V. LABORATORY TEST

The laboratory tests were carried out in order to explore the possibility of the proposed Electricity Cluster-oriented Network. The key technology utilized in the network will be

"Power Router" shown in Fig.5, and then, test results related to the Power Router are given here.

A. Diagram of Test Circuit and Equipment Adopted

Fig.8 shows the laboratory test diagram. In the laboratory, 3-phase, 200V bus bar was split off to formulate a utility-independent network called "Cluster 1" here. Single-phase, 100/200V bus bar connected 60Hz utility via several step-up transformers and the 3-phase, 200V bus bar of utility-independent network were linked with the Power Router. The Power Router consists of a 62kWh Ni-MH Battery and two inverters of ratings, 38kVA(20kW) and 2kVA respectively. The 38kVA inverter was operated under constant-voltage and constant-frequency (CVCF) control, and the 2kVA inverter was operated under constant-power control(APR).

Constant-power load of 9kW was applied during discharge operation of the 62kWh Ni-MH Battery.

The outline of the adopted equipment in the test is shown in Table 4. The equipment and facilities used here are existing ones, and they are not designed for the test. Thus, note that their specifications for Power Router may not be proper for actual utilization.

The diagrams of inverter controllers in the Power Router are shown in Fig.9(a) and (b).

B. Test Procedure and Results

The purpose of the laboratory test intended here is to check Power Router about the operations.

a) At the beginning, Ni-MH battery in the Power Router was charged at the higher level than SOC reference. The frequency of output voltage in Cluster 1 is a little higher than utility frequency f_2 (60Hz).

b) 9kW load was applied in Cluster 1 to discharge the Ni-MH battery in 1-2 hours. Then, the authors observe that the generated frequency f_1 by 38kVA inverter decreases below utility frequency f_2 according to the decrease in SOC of the battery.

c) The authors observe the power flow produced by 2kVA inverter depending on the difference in frequencies, f_1 (Cluster 1) and f_2 (Utility).

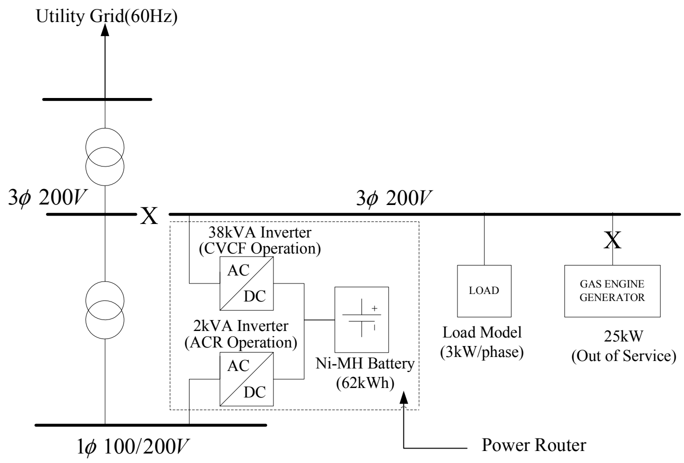
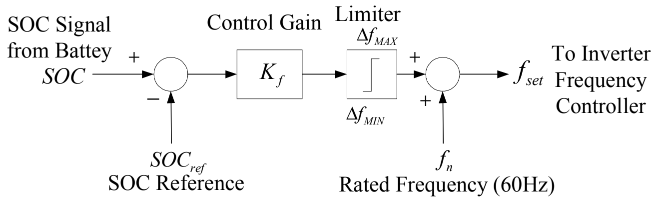


Fig. 8 Laboratory test diagram

Table 4 Rating of adopted equipment in the test

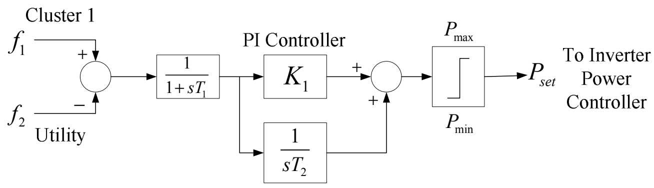
Items	Equipment	Ratings
Power Router	Ni-MH Battery (26 stacks)	Array capacity: 61.2kWh Stack capacity: 2.35kWh Stack voltage: 12V Weight: approx. 120kg
	38kVA Inverter (with DC/DC converter)	DC voltage: 200-500V DC current: -110A~+100A Switching frequency: 16kHz
	2kVA Inverter (with DC/DC converter)	DC voltage: 40-350V DC current: ± 25A Switching frequency: 12.5kHz
Load	Load models with single-phase inverter	Constant-power operation Rating: 0-4kW/phase Acceptable frequency : 40-72Hz



$K_f = 0.04(Hz/kWh), SOC_{ref} = 32.5(kWh),$

$\Delta f_{MAX} = 0.7(Hz), \Delta f_{MIN} = -0.7(Hz)$

(a) Frequency control in 38kVA inverter (CVCF operation)



$K_1 = 0.25(kW/Hz), T_1 = 30(s), T_2 = 99999(s), P_{max} = 1(kW), P_{min} = -1(kW)$

(b) Power control in 2kVA inverter (ACR operation)

Fig.9 Diagrams of 2kVA inverter controllers in the Power Router

Fig.10 shows typical results obtained in the laboratory tests during 1.5 hours.

C. Discussions

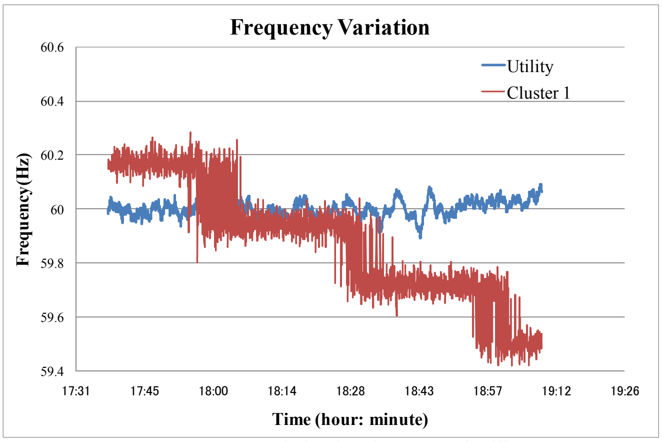
- In Fig.10(a), the observed frequency in Cluster 1 changes in stepwise pattern of about 0.22Hz. This may be due to that the signal frequency around 60Hz and the switching frequency(16kHz) are subjected to synchronous relation. This fact was unavoidable circumstances for authors in applying existing inverter in the laboratory. However, it is not an essential problem to check the Power Router operations, though it may somewhat degrade test quality.
- Fig.10(a) indicates that generated frequency in Cluster 1 can be controlled with control diagram of Fig.9(a) according to the SOC of Ni-MH battery.
- In Fig.10(a) and (b), power flow between Cluster 1 and utility is observed according to the frequency difference in both power systems. When frequency in Cluster 1 is higher than that in utility, direction of power flow is from Cluster 1 to utility, on the other hand, when frequency in Cluster 1 is lower than that in utility, direction of power flow is from utility to Cluster 1. Thus, control diagram of 2kVA inverter in Fig.9(b) was recognized that it works theoretically

proper to improve SOC of Ni-MH battery toward pre-determined reference level.

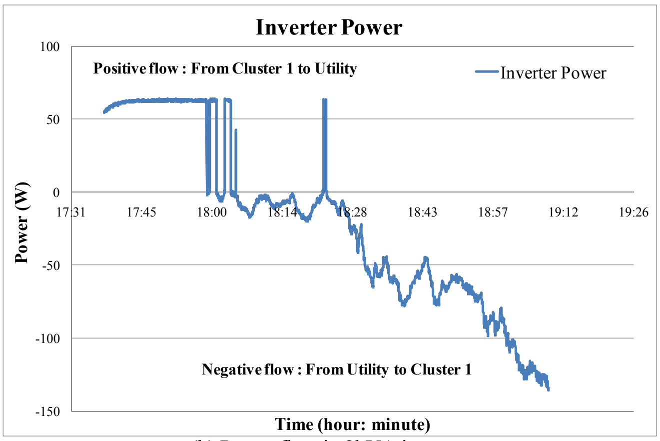
As a whole, it can be said that the Power Router, essential equipment, designed for the proposed Electricity Cluster-oriented Network can work as might have been expected.

VI. SUMMARY

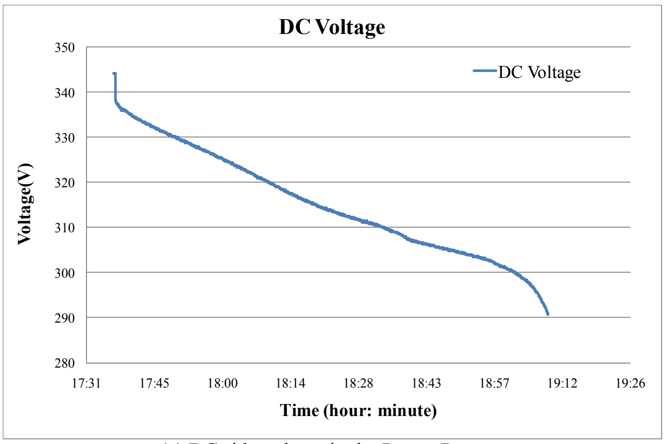
Electricity cluster-oriented network was proposed and the feasibility study to grasp its technical possibility was performed by both computer simulations and laboratory tests.



(a) Frequency variation in Cluster 1 and utility



(b) Power flow in 2kVA inverter



(c) DC side voltage in the Power Router

Fig.10 Test results in the laboratory

As for supply and demand control and the control of interconnection power flow between clusters applied to the proposed Electricity Cluster-Oriented Network, the main points are summarized as follows.

1) Supply and demand control in each cluster

a) BESS is required in each cluster and the inverter (main inverter) is operated under CVCF control mode .

b) The frequency generated under CVCF operation should be variable according to the charged energy of BESS (SOC). When the SOC is more than the target value, frequency set value should be kept at slightly higher than rated frequency. On the other hand, when the SOC is less than the target value, frequency set value should be kept at slightly lower than rated frequency.

c) The above control scheme of cluster frequency may enable output-controllable generations in cluster such as gas or diesel engine generators to control power output according to the local detection of frequency (Automatic Frequency Control).

2) The control of power flow between clusters

a) The inverter is equipped, in addition to the main inverter in BESS, for interconnection between clusters.

b) The inverter for interconnection detects frequencies in two clusters for control of tie-line power flow according to the frequency difference. By doing this, power flow from higher-frequency cluster to lower-frequency cluster can be achieved. Based on the assumption of local production for local consumption in each cluster, the power flow between clusters will be just compensation for excess, and deficiency, in each cluster. This fact will lead to an improvement in supply reliability of the whole network.

It can be said that the proposed Electricity Cluster-Oriented Network is the aggregation of the loosely-coupled, autonomous and independent local networks for demand and supply called cluster, and that expansion in the scale is possible as the need arises. The authors intend to continue with laboratory or field tests in future for demonstration of the proposed Electricity Cluster-Oriented Network.

REFERENCES

[1] K.Koyanagi, N.Saito, T.Niimura, R.Yokoyama, S.Nagata, M.Fujino and Y.Noro, "Electricity Cluster-Oriented Network with Renewable Energy Generation and Battery Energy Storage System", IEEJ-EIT Joint Symposium on Advanced Technology in Power Systems, Rama Gardens Hotel, Bangkok, Thailand, Nov. 26-27, 2009.

[2] T.Sato, K.Koyanagi, R.Yokoyama and K.Nakao, "Study of Load Frequency Control Model for Grid-independent Micro Grid", IEEJ-EIT Joint Symposium on Advanced Technology in Power Systems, Rama Gardens Hotel, Bangkok, Thailand, Nov. 26-27, 2009.

[3] K.De Brabandere, B.Bolsens, J.Van den Keybus, A.Woyte, J.Driesen and R.Belmans, "A Voltage and Frequency Droop Control Method for Parallel Inverters", 2004 35th Annual IEEE Power Electronics Specialists Conference, pp.2501-2507, Aachen, Germany, 2004.

[4] R.H.Lasseter, "Control of Distributed Resources", Paper presented at Bulk Power System Dynamics and Control IV – Restructuring, August 24-28, Santorini, Greece, 1998.