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Internet Style Electric Energy Network Architecture

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Abstract: - We are proposing a new electric energy network architecture with the goal of providing renewable energy sources for future generations. Many small, self-sustaining, autonomic electric energy systems, called "electricity clusters", are networked with DC interface, exchanging electric energy mutually, intermittently and resourcefully. Our proposed Electricity Cluster Oriented Network (ECONET) would network electric energy systems by means of an Internet style architecture. We would like to describe the abstract design of ECONET, trial of a miniature tip, simulation, and a clearer system of the architecture than was presented in our last paper.

Key-Words: - Dispersed Generation, Photovoltaic, Renewal Energy, Cluster, Electric Network, Router, DC

1 Introduction

Electricity is the form of energy that characterizes modern civilization and culture. Especially in the information technology era, electricity is essential to most industries, and is vital to human survival. As fossil fuels become more scarce, the sources for electricity are becoming more expensive. Furthermore, mining, burning and other activities associated with the acquisition and use of fossil fuels can create environmental problems such as contamination and may be linked to global climate change. While nuclear energy may not contain the risk of climate change, there are other negatives associated with its use.

Under existing conditions, renewable energy sources (RES) have the most potential for electric generation, and the research and development(R&D) is quite active. Most of them, however, have focused on dispersed generation (DG), and most studies on electric network have been based on a conventional grid electric network, concentrating on issues such as keeping stability and downsizing to micro grid.

2 ECONET architecture

ECONET is a network intended to accommodate RES DG as the main source of electricity [1].

2.1 Distinction from energy sources

Since RES DG cannot ensure electric generation capacity, stability, continuity or controllability. From another viewpoint RES are ubiquitous and energy density is low. As RES DG is distributed and small scale, and is well suited to generate electricity at the point of demand.

The grid system was designed to transmit and distribute electric power from large scale electric generations by stable and fully controllable energy sources like fossil fuel combustion and nuclear fission, so the costs in keeping a grid stable would be very expensive by retrofitting to accommodate a large amount of RES DG.

We think that a new electric energy network architecture is necessary to enable sharing of electricity from RES DG.

2.2 Electricity clusters and the network

First we would like to introduce the concept of an "electricity cluster". An electricity cluster consists of dispersed generators, electric storage and appliances in as a total self-contained electric energy system. This is a small "distributed electric energy system" limited by electric capacity and/or regional conditions depending on scale. RES and electric consumption are capricious in each place, so electric storage is very important. Not only to level off fluctuations in generation, but also consumption demands.

Each cluster is independent, autonomic and self-sustaining. However shortages and/or surpluses of electricity may occur.

Many varied electricity clusters are connected to each other, so the set forms an ECONET (see Fig.1). The network carries electricity only to exchange between clusters in cases of shortage or surplus bi-

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directionally, while a grid transmits all electric power to consumers one-way.

The exchange of electricity in ECONET should be a "best effort service", each cluster has electric storage to survive. Network trouble in ECONET will not always cause a blackout, because each cluster is autonomic, has electric generation/storage and can control demand in the cluster. ECONET should be "loosely coupled", while the conventional grid is "tightly coupled". Loosely coupled means that trouble occurring in a cluster will not influence other clusters, ECONET does not contain a single point of failure to allow a catastrophic system-wide breakdown.

Therefore, ECONET will provide secure electric energy systems in the event of disasters or terrorism attacks.

2.3 Electricity Router

The cluster is a node, and the transmission lines between such clusters are links of the network. Every cluster has an "electricity router" [2].

The main functions of the router are controlling the exchange of electricity among clusters, and serve as a switching point in the exchange.

The router is composed mainly of a DC/DC converter (DDC) that has control functions. By controlling the DDC, an electric circuit may be easily switched. DDC can function as circuit breaker and current limiter without loss. A router has additional functions, which include charging and discharging of electric storage, and maximum power point tracking (MPPT) for Photovoltaic(PV).

All of these functions are made feasible by the technology of power electronics components, which achieve high voltage, large current and limited loss at a reasonable cost in the last few decades.

The electricity exchange negotiation is via a digital

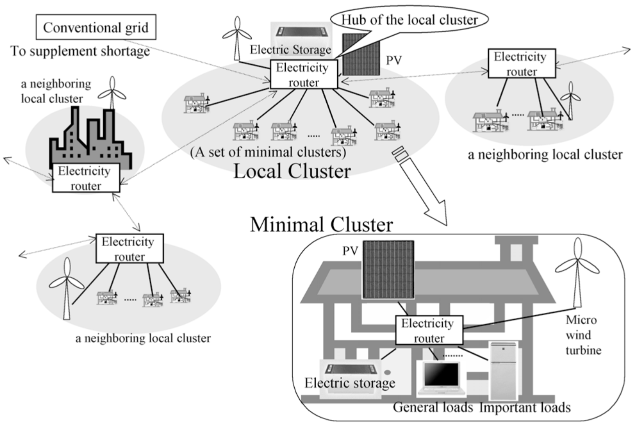

Fig.1 ECONET, an inter-electric clusters network

data communication network that is independent from the voltage or phase of the power transmission line. The Internet is sufficient for the communication between the routers. With ECONET, clusters exchange electric energy [kWh] instead of electric power [kW], so some delay in an "Internet best effort service" is acceptable in the negotiation.

One of the key advantages of ECONET using the Internet is inexpensive and more than sufficient to enable the system, as compared to what is necessary for conventional grids and micro grids. A grid is controlled through the simultaneous equalization power [kW] of supply and demand and it needs real time communication to manage the power flow.

2.4 Layered structure

An electricity cluster may have a layered internal network structure. Adequate numbers of clusters are networked to form a set. The set is assumed to be a cluster in the higher layer.

The most primary system is called a "minimal cluster", as shown in Fig.1, which is an image of a standard residence, an office or a small factory.

The elements in the minimal cluster are many types of electric appliances, feeder lines, electric storage, generators and an electricity router. The electricity router and storage in a minimal cluster also take responsibility of feeding the electric appliances inclusive of the peak power [kW].

About 10 to 10k minimal clusters will be networked as a "local cluster". A local cluster should provide electric generation or grid connection to supplement electric energy shortages for minimal clusters in the local cluster. Electricity router and electric storage facilities also should be equipped in the hub of a local cluster in order to exchange electric energy between neighboring clusters and minimal clusters in the event of greater demand or to supplement demands in the event of a minor failure of a minimal cluster in an adjoining cluster.

A local cluster can be a village, town, city, large-scale condominium, and an industrial complex. Many types of minimal clusters mixed into one local cluster in order to balance electricity requirements in the cluster as a whole.

2.5 DC Interface

The interface between clusters should be direct current (DC), because transmission of electricity is intermittent and fluctuates greatly in RES DG. As each cluster is autonomic and highly independent, it

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maybe very difficult and even inefficient for every cluster to synchronize operation with an alternating current (AC) power interface.

Electricity from PV, to/from electric storage is DC, and most modern electric appliances need DC supply. Almost all information appliances consist of DDC, supplied AC100 ~ 240V / 50 ~ 60Hz rectified to DC140 ~ 300V to feed the DDC. Efficient modern air conditioners have a variable voltage variable frequency (VVVF) converter to obtain specified torque and cycle in an induction motor, and DC is fed to the VVVF. An induction heating cooker and a high frequency driven fluorescent light also need DC.

Using a DC interface and feeding DC can reduce loss with the decrement of DC/AC conversion, rectification/smoothing and transmitting Var.

2.6 Network topology

Generally, the network topology of ECONET depends on implementation requirements, especially power scales, interface methods and cost performance. With a DC interface in ECONET, a "star type" or "partial mesh type" topology may be better than a "bus type" topology (see Fig.2).

A conventional AC grid uses a "bus type" network topology, with all electric power generation and consumption tightly coupled with each other in parallel. In bus network topology, trouble at any node or link influences other parts, which are connected to the troubled part. A circuit breaker is the most important network equipment for cutting off the troubled part from the grid.

A DC circuit breaker is more expensive than an AC, which makes it difficult to build DC systems in conventional grid architecture.

A DC interface in an ECONET system would be composed of "point to point DC power transmission technology", with a star and/or partial mesh topology instead of bus topology. As a substitute for a circuit breaker with mechanical contacts, DDC control should be used to shut down troubled circuits (i.e., a "gate block technique"). A DC circuit breaker or fuse is still necessary for various kinds of protection for DC sources like electric storage.

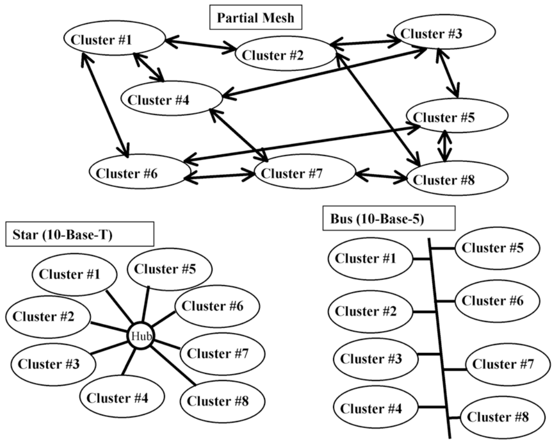

Fig.2 Types of network topology

3 Abstract design

In an abstract design for a trial of a miniature tip of an ECONET model, autonomic clusters and their network, exchange of electric energy shortages and surpluses, data communication to negotiate exchanges and DDC gate block technique for switching are key issues. And an electric double-layer capacitor (EDLC) was used in the miniature tip because it has potential for electric storage, but ordinary chemical batteries could also be used.

3.1 Abstract design of a local cluster

To illustrate the design of a local cluster, the router at the hub of the cluster and one minimal cluster has been clipped from Fig.1 to design the miniature tip.

In the block diagram shown in Fig.3, the lower half is a minimal cluster and it becomes a master in the control algorithm. The upper half is a router at the hub of the local cluster (hub router). The hub router becomes a server. The miniature tip is intended to test the following algorithm for exchanging electric energy between routers.

As the miniature tip also is intended to demonstrate

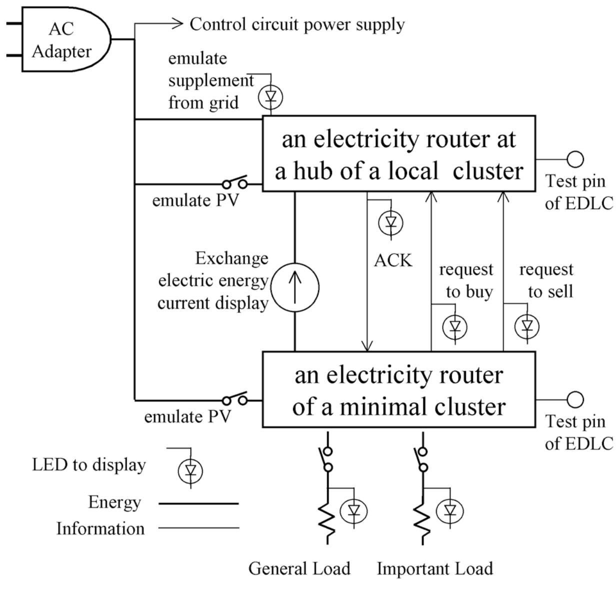

Fig.3 The block diagram of a local cluster

concept of ECONET architecture, it has three indicators to display the states of digital signals (request to buy, request to sell and acknowledge), and a current meter to display the electric power flow according to the algorithm. Naturally, the power line and the current meter are bi-directional.

3.2 Abstract design of a hub router

Fig.4 shows a block diagram of a hub router. An EDLC is used for electric storage. Energy stored in a capacitor depends on the voltage of the capacitor ($e=0.5CV^2$, e: energy [J], C: Capacitance [F], V: Voltage [V]). The voltage of an EDLC is dynamically more variable than a chemical battery.

Charging electric energy efficiently to an EDLC, the DDC should operate in an output current control mode, but not an output voltage mode, because the voltage of an EDLC fluctuates widely. "A" and "P" in Fig.4 are DDCs with output current control mode. (PV is emulated and MPPT was not installed in the miniature tip for the first trial).

In the EDLC's discharging operation as a constant voltage in exchange, DDC operates as a voltage regulator, like "V" in Fig.4.

These DDCs also have an ON/OFF control input controlled by a digital "controller", as shown in Fig.4.

The charger "P" shown in Fig.4 is ON while PV generates electricity. The controller makes the charger OFF when electric storage becomes full while PV generates electricity, in order to protect EDLC from overvoltage.

The algorithm is installed in the "controller" in the router. Though the algorithm is very basic in this first trial, it is new in the exchange of electric energy, and is based on (remaining) electric energy storage.

"A" in Fig.5 is a process to sell (send) electricity to a minimal cluster in the local cluster. Receiving a "request to buy (electricity)" from a minimal cluster that is a master, the router in the hub of the local cluster acting as the server replies with an ACK (acknowledge) to the minimal cluster and outputs

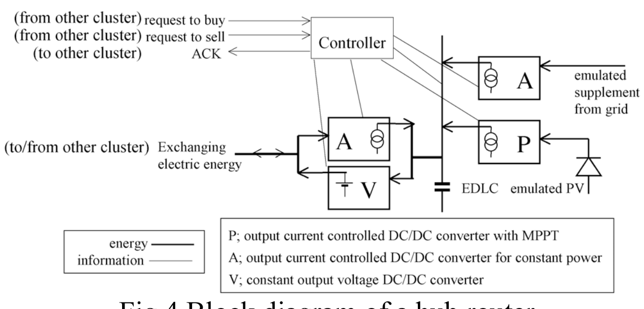

Fig.4 Block diagram of a hub router

electricity when even a small quantity of electric energy remains in the hub.

"B" in Fig.5 shows a "request to sell" from the minimal cluster, and the router replies with an ACK to the minimal cluster and accepts electricity when electric storage at the hub is not full.

"C" in Fig.5 shows the process for supplementing electricity from the grid, when the local cluster senses a shortage. The "from grid" can be replaceable with DG like biomass thermal, fuel cells, wind and micro hydro generation.

3.3 Abstract design of a minimal cluster

Fig.6 shows a block diagram of a minimal cluster. Basically the same as in Fig.4, but the minimal cluster has some electric appliances and the router in the minimal cluster functions to feed the appliances loads. The algorithm of a router in a minimal cluster is different from a hub router, because the router in a minimal cluster becomes a master.

The Fig.7 "E" is established to sell electricity when the electric storage is full in the minimal cluster. Sending a "request to sell" to the server, which is the hub router in the local cluster, waiting for an "ACK" signal, then the router in the minimal cluster starts outputting electricity to the network.

"F" in Fig.7 shows a process to buy electricity when the minimal cluster senses a shortage of electric energy. When electric storage reaches a specific low level, the router sends a "request to buy" to the server, and waits for an "ACK" signal. If the minimal cluster does not receive an "ACK", it is not able to get.

"D" is the priority process to feed loads. When the energy storage is enough, all loads (appliances) are

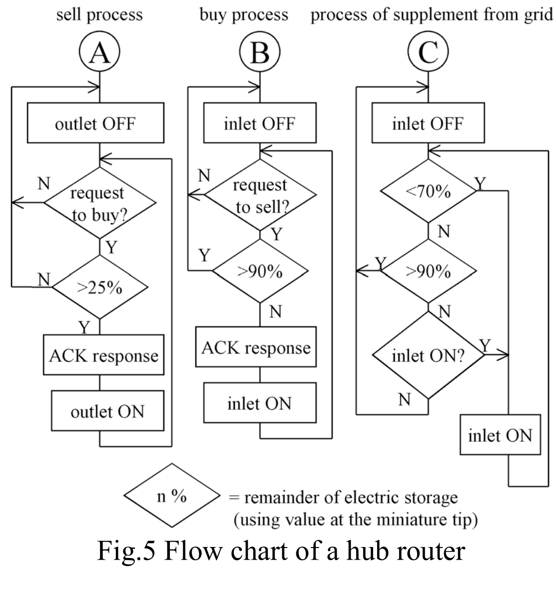

Fig.5 Flow chart of a hub router

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fed. If storage is not at a high level, only important loads (like refrigerators) will be fed. The control circuit also must be fed to survive as a minimal cluster in the network to get electricity when it becomes available.

3.4 Scaled down miniature tip

To stage a trial of the miniature tip of ECONET within a reasonable budget, the scale down has been assumed at 1/100 for voltage [V], current [A] and time[s], so power [W] and capacitance [F] are on 1/10,000, energy [kWh] is on 1/1,000,000.

The miniature tip and its installed algorithms work well, and could help demonstrate ECONET to electrical experts and the general public.

4 Simulation

Numerical simulation of a local cluster unit has been done based on an algorithm exchanging electric energy [kWh], and given a reduction rate to disturb grid interconnecting as a local cluster.

4.1 Modeling for simulation

Base data for the simulation was obtained from "KOBUNAKI Ecology Village" which is a real development plan by a Non Profit Organization in Japan[3]. In approx. 15ha, 370 residences (typical 120m^2, two-storied, total amount 39780m^2 floor space) and low profile office(one to three storied, total amount 7250m^2 floor space) in the central zone are arranged. In this simulation, a hub of the local cluster assumed using the central office zone both as.

Each residence assumes equipped 4kWpeak PV (approx. 30m^2), which is reasonable to install to the above typical residence. The office also assumes equipped PV with same ratio of a residence one. PV electric power generation unit data is converted from our actual measurement data for years.

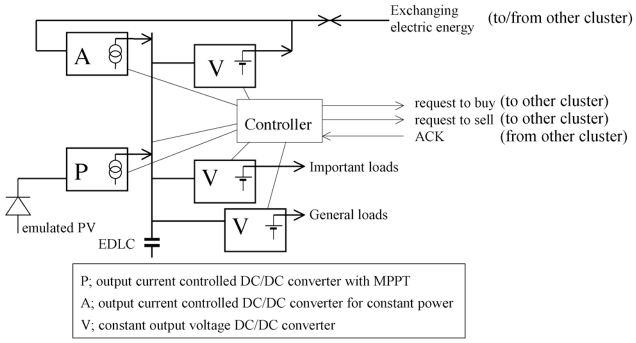


Fig.6 Block diagram of a router in a minimal cluster

Each residence has electric storage capacity assumed as average of one-day consumption (typical 12kWh), and the office also has 3MWh electric storage in same manner of residence. The electric storage is not dependent upon a means.

Unit data of standard electric consumption is converted from the source book [3], with COP (coefficient of performance) = 3 for heating and cooling.

4.2 Results of simulation

The simulation has been executed by one-minute interval, at 9 cases of electric generation and consumption during the various seasons winter, summer, intermediate seasons as well as varying conditions such as fair, cloudy, and rainy weather.

The toughest case was the intermediate season and fair weather, because it resulted in the lowest consumption and the highest generation (Fig. 8). Using the above assumed condition parameters, the minimum transmission capacities were 1.8kW for minimal clusters and 500kW for a local cluster, in order to save all of the generations. The values can be reduced by forecast of electric generation and consumption.

The worst case of disturbance interconnecting to a grid also was the intermediate season and fair weather. In the case, reduction ratio of the disturbance was calculated to 78%, as compared with simple interconnection to a grid.

5 Next R&D issues

With regard to the system design, the most important issues for the next R&D efforts are safety, preservation and protection of the DC interface

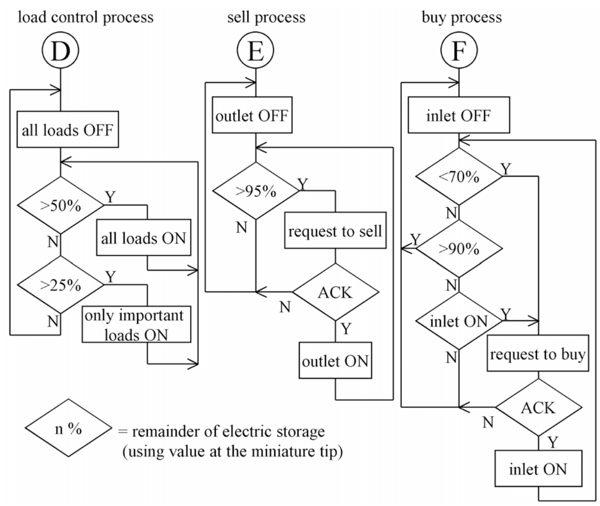
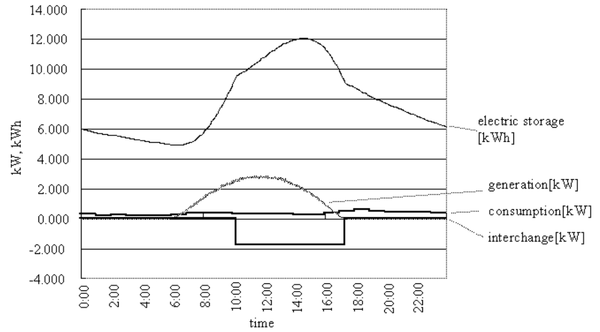
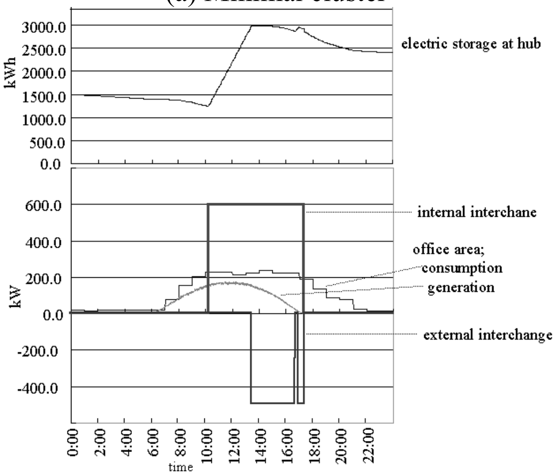


Fig.7 Flow chart of a minimal cluster router



(a) Minimal cluster



(b) Local cluster

Fig.8. Simulation on a clear day in a middle season

mainly for hardware [5]. Establishment of the exchange rules is necessary for the specifications and design of the software [6]. Although this paper presents the primary algorithm, more study must be done on the algorithm to exchange electric energy, according to forecast RES DG and electric demand.

At that point, real scale prototyping and actual field experimentation can then be conducted.

ECONET architecture is based on electric storage, RES DG and power electronics. We believe that these are enough to compose ECONET real systems, but expensive or a little expensive. The next R&D issues should be set on "element devices" to reduce cost of EDLC and PV. Wide gap (SiC) semiconductor devices will be able to reduce loss, even for silicon devices that consist of an electricity router.

6 Conclusion

In order to ensure the survival of future generations, we must eventually shift energy sources generating electricity to RES, and building electricity network that can accommodate full RES DG. ECONET is a totally new architecture to share ubiquitous electricity of RES with ubiquitous electric demand.

In the 21st century, the global village has the challenge and opportunity to turn an "ecological economy" into a high-quality growth economy as we move away from a fossil fuel based economy to sustainable energy sources.

7 Acknowledgements

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(Yoshihiko Matsumoto is also with IRI.)