Digital Grid: Communicative Electrical Grids of the Future

Rikiya Abe, *Member, IEEE*, Hisao Taoka, *Senior Member, IEEE*, and David McQuilkin, *Member, IEEE*

***Abstract*—To support a high penetration of intermittent solar and wind power generation, many regions are planning to add new high capacity transmission lines. These additional transmission lines strengthen grid synchronization, but will also increase the grid's short circuit capacity, and furthermore will be very costly. With a highly interconnected grid and variable renewable generation, a small grid failure can easily start cascading outages, resulting in large scale blackout. We introduce the "digital grid," where large synchronous grids are divided into smaller segmented grids which are connected asynchronously, via multileg IP addressed ac/dc/ac converters called digital grid routers. These routers communicate with each other and send power among the segmented grids through existing transmission lines, which have been repurposed as digital grid transmission lines. The digital grid can accept high penetrations of renewable power, prevent cascading outages, accommodate identifiable tagged electricity flows, record those transactions, and trade electricity as a commodity.**

***Index Terms*—Smart grid, renewable energy, solar, ac/dc/ac converters, BTB, power electronics, transmission lines, IP address.**

I. Introduction

TODAY'S ENERGY grid has been developed with extensive interconnections and grids often spanning continents. The purpose of this interconnection is to improve reliability through redundancy. However, in some ways, this interconnection increases the risk of wide area failures because any imbalance can be propagated quickly over an ever widening area.

Increasing proportions of renewable and variable energy generation cause increasing fluctuations which will become, at some point, unmanageable using the current grid architecture.

If we can envision a future world where higher penetration of renewable energy is expected, we can also forecast new ways to use electricity that are not possible with the current grid design.

In order to accept increasing penetration of renewable energy into the current power grid, it is important to ***measure*** *power levels throughout the grid, as is envisioned in many smart grid designs*.

However, to relieve the stress caused by such intermittent renewables to primary generation such as nuclear and thermal, we need to ***control*** *power flows directly* throughout the highly interconnected grid.

This paper describes the "digital grid" where a wide-area synchronized power system is subdivided ("digitalized") into smaller or medium sized power systems. Subdivided grids called "digital grid cells" (simply called "cells," hereinafter) are connected together ***asynchronously*** via "digital grid routers" (DGR). DGRs can send discrete power packets over existing transmission lines to any location using multileg voltage source converters, with high frequency modulation, combined with IP address information. Within the subdivided cells, "digital grid controllers" (DGC) coordinate with DGRs to absorb, consume and generate the discrete power packets associated with wind, solar, load and energy storage. DGRs also tie a number of cells to the main (traditional) grid and play a roll of a shock absorber so that intermittent renewables in cells will not affect the main grid. DGRs will also support the main grid stability via use of energy storage. The energy transactions through DGRs and DGCs can be recorded using embedded data storage and collected by certified service providers along with many properties such as location, time, generation source, price and including CO_2 credits, RPS value, and green certificates. This new grid is thus "digitalized," where rather than allowing energy to flow across the grid relatively uncontrolled from source to destination, it is now discretely controlled by digital means across each segment. We would like to envision a digital grid where energy use enables a better world rather than being a harbinger of environmental damage.

A. Renewable Energy Potential

According to the U.S. Department of Energy, the solar energy resource from a 100-mile-square area of Nevada could supply the United States with all its electricity (about 800 GW), using modestly efficient (10%) commercial PV modules [1]. As Fig. 1 shows, there is a large amount of potential energy from solar power every year compared to the energy which can be derived from the entire known reserves of fossil fuels and uranium ore [2]–[4].

With suitable energy storage, solar energy could supply a significant portion of the energy needs of the world. Rather than restricting energy usage in the name of environmental protection, a solar powered grid would make energy available for new applications and benefits. Solar energy can also be a solution to the problems of fresh water supply, food production, liquid fuel synthesis, etc.

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R. Abe is with Advantage Partners Socio-Strategic Investment Laboratory, Graduate Course of Technology Management for Innovation, School of Engineering, University of Tokyo, Tokyo 113-8656, Japan (e-mail: abe-r@tmi.t.u-tokyo.ac.jp).

H. Taoka is with Graduate School of Engineering, Electrical and Electronics Engineering, University of Fukui, Fukui 910-8507, Japan (e-mail: taoka@u-fukui.ac.jp).

D. McQuilkin is with Kyumaru Pacific Alliances LLC, Cupertino, CA 95014-2358 USA (e-mail:dmcq@kyumaru.com).

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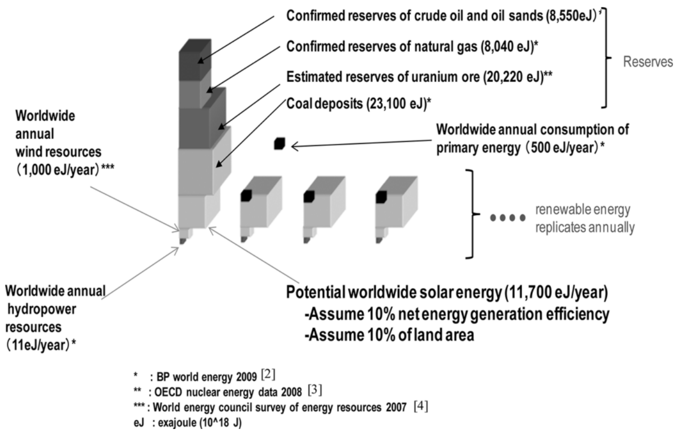

Fig. 1. World energy consumption and energy sources (produced by Rikiya Abe).

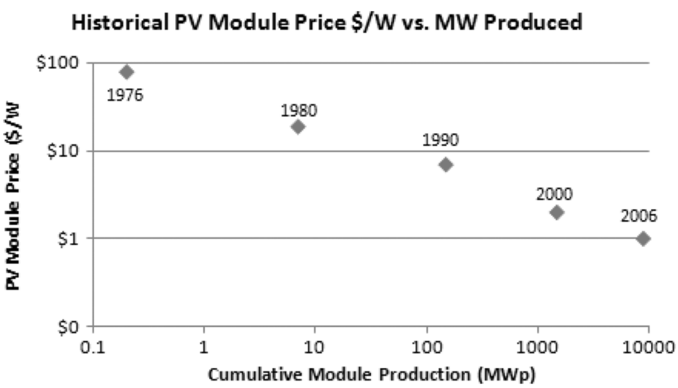

Fig. 2. Historical PV module price versus MW produced [15].

B. Energy Storage Cost

The primary barrier to deployment of storage is that of cost, but as PHEVs and EVs enter the market, there will be sustained motivation to improve storage technologies and lower the prices [5]. These batteries in vehicles are likely not suited for grid-scale energy storage, but many papers indicate that vehicle to grid (V2G) will be applied for stabilization of the grid and supporting large-scale renewable energy [6]–[14].

A European Union Joint Research Committee found a close relationship between annual production rates and cost reduction as shown in Fig. 2, where the cost of PV modules dropped 22% for each doubling of cumulative module production [15].

Data storage prices for computers have shown an even more dramatic drop as production increases, with prices dropping from $50/megabyte in 1986 to less than $0.01/megabyte in 2008 [16].

The initial sales of PHEV and EV are supported by government subsidies, similarly as was the case with the initial sales of PV modules. As the market develops, the prices naturally become lower and the subsidies also decrease, until the point where mass availability enables commodity pricing, following the model of computer components.

We therefore can forecast that energy storage prices will likewise exhibit continuing price reductions as technology and production methods improve and as production volume increases.

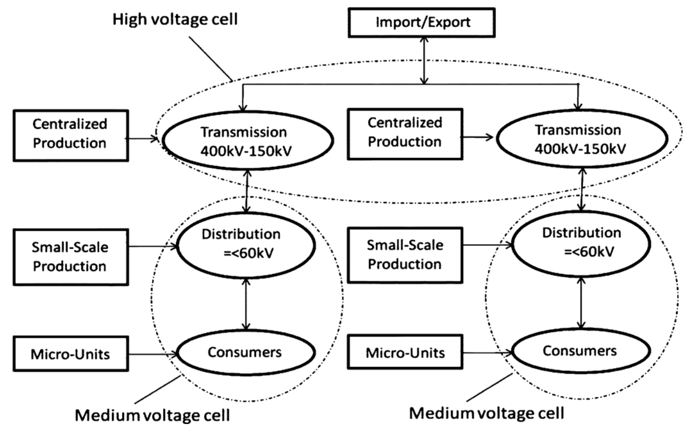

Fig. 3. Cell concept introduced in Denmark [24].

C. High Proportions of Renewable Energy

In recent years, electric power generation from renewable energy sources such as wind and solar has accelerated due to efforts to reduce the impact of climate change and escalating fossil fuel prices.

Europe has set a target of 20% of final energy consumption to be produced by renewable sources [17], the United States has set goals of from 10% to 30% renewable energy [18], and Japan has set a target of 28 GW photovoltaic (PV) generation by 2020 and 53 GW by 2030 [19], which is more than one fourth of Japanese peak demand.

However, a 7/2007 report "Low Carbon Power Distribution System Conference" in Japan [20] asserts that a maximum of only 13 GW PV could be installed with the current power grid and planned improvements by 2020.

To utilize large proportions of renewable energy without the risk of wide area failures, there is a strong need to develop a new electric power grid, and various approaches are being considered [21], [22].

One approach is a smart grid design, where demand-side management of power usage is put into effect through a parallel information network [23]. However, demand-side management does not solve the problems of power flow caused by impedance which is relatively static in the traditional grid, but becomes dynamic in a distributed generation grid. With renewable energy, the generated energy is inserted at designated points in the grid, however, the generated energy varies unpredictably. This makes it increasingly difficult to manage the power flows throughout the grid, and simple demand-side management does not resolve this problem.

To avoid this issue in Europe, where there is increasing deployment of renewable energy, a "CELL" concept shown in Fig. 3 is being developed, where the grid is subdivided by voltage-class (making a local area a "cell"), whereby each cell provides balanced supply-demand, and tries to avoid the reverse power flow to the higher voltage grid [24]. Nevertheless, it still might be difficult to avoid very fast cascading outages by using this control method.

In this paper, a new type of power system is proposed where a wide-area synchronized power system is subdivided into smaller or medium sized cells, and connected through asynchronous coordination control.

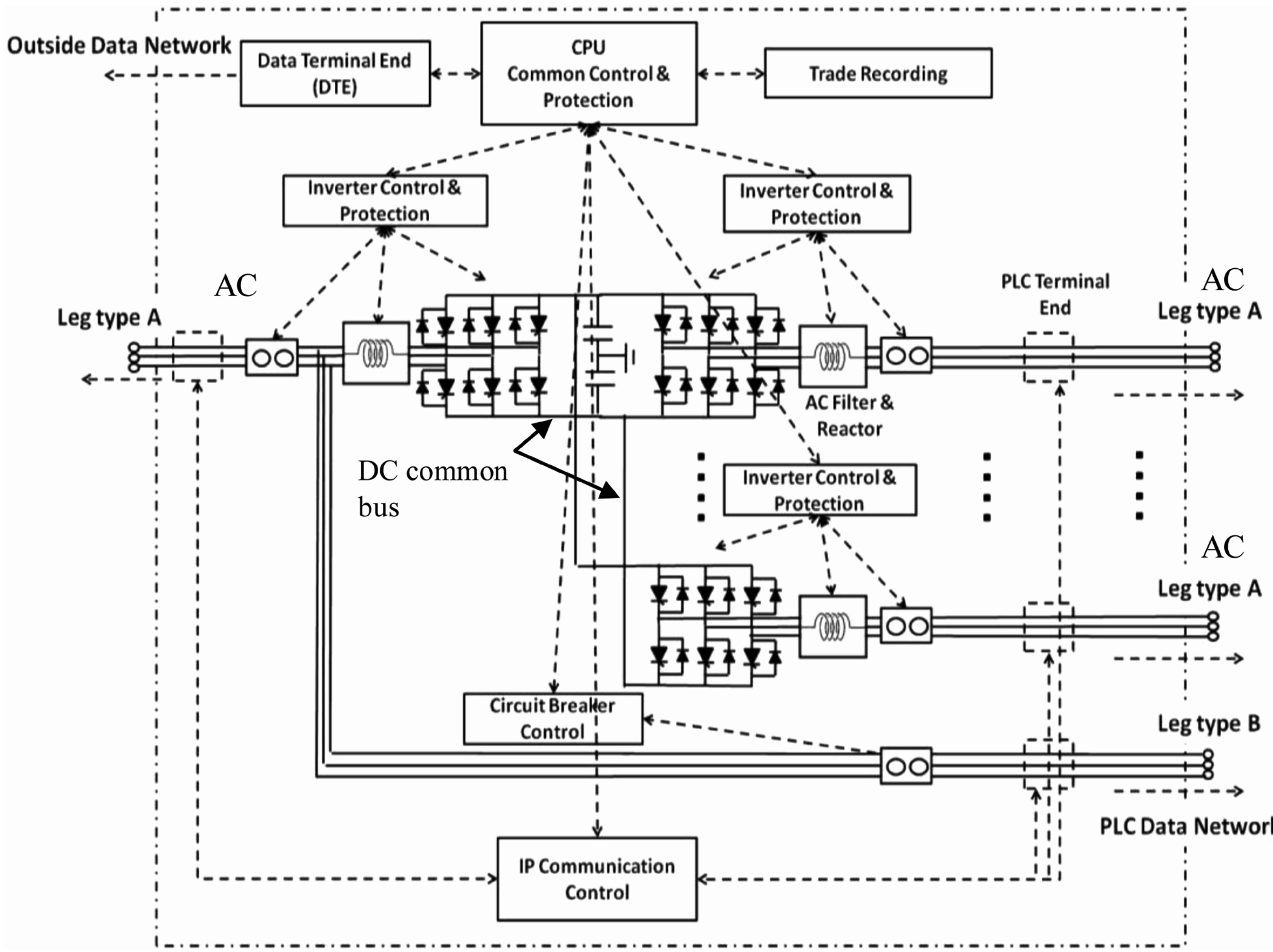

Fig. 4. Digital grid router (DGR).

Asynchronous coordination which is introduced here is a method of exchanging power by connecting separate unsynchronized ac subgrids using multileg ac/dc/ac conversion by power semiconductors with communication, called the digital grid router (DGR), which we invented as shown in Fig. 4.

Each leg of the DGR has three phase ac/dc conversion power semiconductors such as insulated gate bipolar transistor (IGBT) or MOSFET (for lower voltage applications) and connected to a common dc bus.

High frequency pulse width modulation (PWM) controlled by a CPU and/or digital signal processor can establish "voltage," as well as "phase," independently from that of the connected cell. The differences in voltage and phase over the phase reactor will enable bidirectional on-demand active power flow. Reactive power can also be controlled as desired as shown in Fig. 10(B).

Some existing similar examples of asynchronous coordination are back-to-back (BTB) systems or loop power controller (LPC) systems, both of which use ac/dc/ac conversion. These illustrate asynchronous power exchange between two cells.

Many high voltage direct current (HVDC) applications from a few hundred MW to 1000 MW are in operation now, where IGBT-type ac/dc conversion stations are identical to one leg of the DGR in Fig. 4 [25].

The DGR enables coordinated asynchronous power exchange among more than three cells simultaneously, explained in detail in Section VII, enabling a wide variation of connection points and power capacities.

Several DGRs enable coordinated operations and transport the power to the remote cells like data packets on the Internet, using similarly designed routing algorithms.

The cells can use the existing transmission lines for asynchronous power coordination among multiple neighboring cells. The size of a cell can be as large as one state, medium as in the size of cities, and the smallest cell example might be a single house. A smaller cell can exist within a larger cell, making a fractal structure.

These cells can be directly connected to the ordinary synchronous grid and can be connected asynchronously at the same time.

The cell can be operated in a stand-alone mode and is freed from the conventional restriction of exactly matching generated power with demand each second, if each cell has sufficient energy storage. This illustrates the concept that in the existing grid, the value of energy is inherently tied to the time it is produced as well as the time it is required, or the time-related value of electric power.

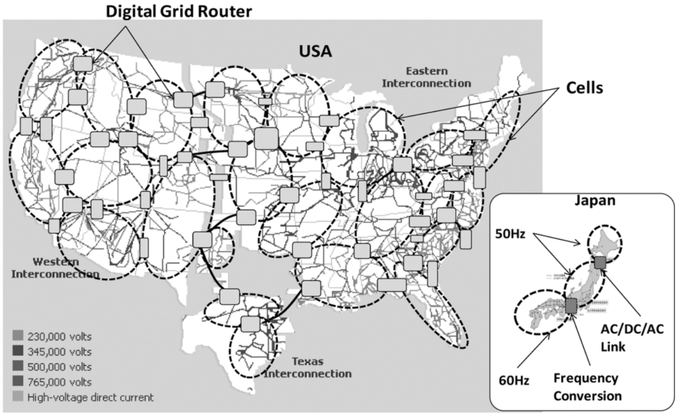

Fig. 5. Image of digital grid in the United States versus Japanese grid.

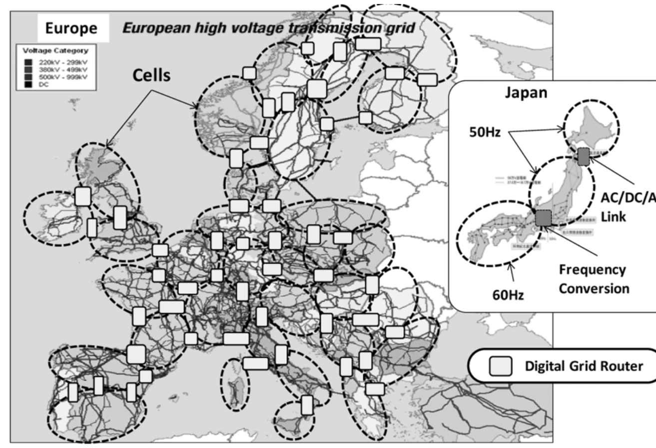

Fig. 6. Image of digital grid in Europe versus Japanese grid.

In order to remove this time-related value of energy, and enable commodity pricing of energy, a digital grid is proposed.

The following is a description of our proposed digital grid.

II. Features of the Digital Grid

A. Image of the Digital Grid

Japan is divided into three independent grids and connected with ac/dc/ac power conversion stations, which can export and import power as demand requires. The peak demand of the grid in the north is 5.4 GW, while the peak demand for the eastern grid is 113 GW and peak for the western grid is 66 GW. The capacity of each conversion station between north and east is 0.6 GW and that between east and west is 1 GW. Each grid is maintained internally at a constant frequency level, which is 50 Hz $\pm$ 0.2 Hz in the North and East, and 60 Hz $\pm$ 0.2 Hz in the West.

If we apply the same concept to the grid in United States whose peak demand is 800 GW, it could be subdivided from approximately 8 to 130 cells with connections between the cells altogether via ac/dc/ac DGRs as shown in Fig. 5. (Map of Japan is to the same scale.)

The European region already has a digital grid like network; however, more aggressive segmentation and asynchronous ac/dc/ac coordination is recommended. Fig. 6 is the image of the digital grid application in Europe. This concept would stabilize the European grid and enable it to deploy more renewable generation.

Segmented grids (cells) are connected by DGRs, which can export and import power among multiple cells at the same time through the existing transmission lines which have been converted to digital grid lines. Segmentation will increase total grid robustness due to the redundancy of power routes and because the segments are no longer directly connected, limiting any failure to the originating cell. All electrical devices, including generators, batteries, even smaller home electronics, etc., in a digital grid can be IP addressed and controlled by or through digital grid controllers (DGCs).

IP controlled power includes unique identification which can be recorded for each power transaction, and thereby we can distinguish power flows from one another, a capability not available on the existing grid or proposed smart grid

B. In the Case of Developing Countries

In developing countries, it is common to have independent locally generated power systems for each town or city. It can be said that these independent grids are unconnected cells. Large investments and a extended installation periods are prerequisites for them to be connected as part of a stable traditional synchronous grid, composed of large scale power stations and high voltage transmission lines. Since these cells are difficult to connect synchronously, they can be connected through asynchronous coordination, that is, DGRs. The connecting transmission lines can be set up as necessary because there are no existing transmission lines among cells. These transmission lines can be installed segment-by-segment as the pairs of cells seek cooperation and exchange of energy. Therefore, the investment more easily matches the incremental investment strategy that is common in developing regions.

C. Features of the Digital Grid

The proposed digital grid has the following features.

1) Independent cells with mutually unsynchronized phases and frequencies are connected using DGRs composed of power converters and coordinated transmission lines, which exchange electric energy between selected cells by supplying specified energy directly through power converters to the designated end point selected by an address as shown in Fig. 7. A DGR may have two types of leg: type A (with power conversion) and type B (without power conversion). Each point-to-point connection is composed of a set of legs, one of type A and the other of B plus the power line. This avoids the undesirable double conversion of power.
2) In each synchronized system within a cell, power equipment control devices called digital grid controllers (DGCs) are used to transfer information and thereby to control power equipment such as generators and energy storage devices.
3) Each DGR and DGC has a CPU, memory, data storage, and network communications, and is assigned a unique IP address and communicates using an IP protocol like on the Internet.

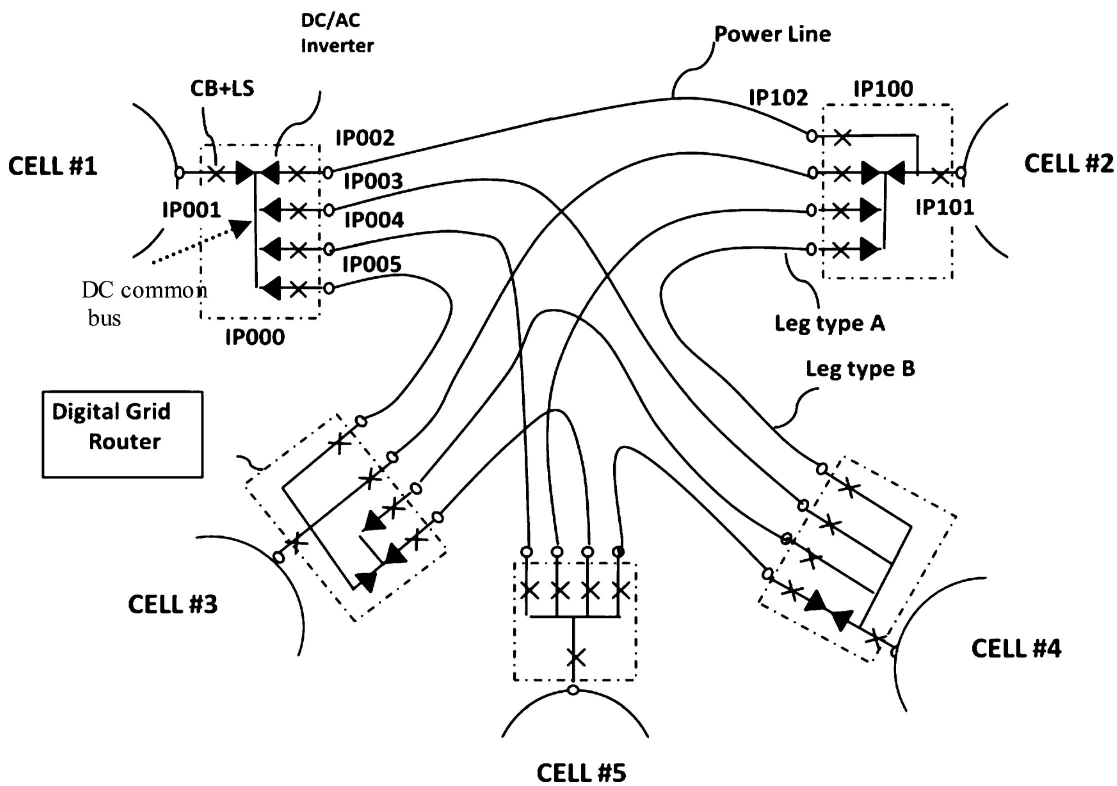

Fig. 7. Interconnection of cells with DGRs.

4) For communications, if the power transmission line is used, power and information can be integrated on a single line [26]–[28], or an external data network may also be used.

III. Functions of the Digital Grid

A. Support for High Penetration of Renewable Energy

When integrating a large proportion of renewable energy, the existing power grid is limited because the power fluctuations grow too large to maintain synchronization over such a large area. By separating the power grid into cells, the fluctuations of renewable power are managed within the cell. The fluctuations of one cell cannot affect other cells because each cell is separated by ac/dc/ac conversion, thereby preventing a large scale blackout.

B. Grid Stability and Redundancy

Power can be acquired using other paths if some lines have faults because a number of paths are available among cells, and it is not limited to the primary path and backup path. In such asynchronous coordination, small or medium sized cells can be considered to be "nodes" and the connecting transmission lines as "links," thereby much of the communications network theory and technology can be applied. Theoretically, N nodes have $1/2\mathrm{N}(\mathrm{N}-1)$ links. This makes the wide area grid robust against major failure. This robustness is similar topology to the stability and redundancy of the Internet [29].

C. Ad Hoc Flexibility

For developed countries with existing operational infrastructure, it would be prohibitively expensive to replace the entire power grid so as to convert to the digital grid. However, it is possible to make it partially "celled," unlinking a portion from the existing power grid, and have both synchronous and asynchronous connections, or connecting a commercial or industrial power system to the existing power grid synchronously, or to separate a residential power system into an asynchronous cell.

Differently from discussed microgrid interconnections [30]–[34], power can be sent to the IP addressed target at will through DGR. The digital grid can coexist with the conventional power grid.

In developing countries and other regions where cell-like subgrids are scattered, the digital grid can be used to connect these scattered cells to make a more robust national or regional grid. Therefore, it is possible to link cells into a digital grid scheme gradually, based on the needs and the budget.

D. Digital Power Trading

The DGR enables the delivery of electricity to the destination cell, passing through several intermediate cells, by using an address and routing capabilities, as explained in detail in Section VII. The energy is tagged with identification information including generation source, route of delivery, storage device (if any) and end user (energy consumer). When energy storage is used, the usual restriction that energy must be produced and consumed at the same time is relaxed. Storage enables flexible commercial trading so energy can be reserved for future use, and the time of delivery can be selected by the energy user. The digital grid dramatically improves the value of energy storage and makes it possible to have a business platform for a new energy trading business. Free market commodity trading mechanisms can be applied for electricity trading which will accelerate investment in such new systems.

E. Merging Information and Electric Power

The digital grid router and the digital grid controller are addressable and use outside data networks as well as power line communication (PLC) [26]–[28]. Both power and information are transmitted over the same physical line when PLC is used. This integrates the energy and the information physically, and offers the benefit of increasing robustness because it prevents cases where information of a transaction is delivered via the external data network but the energy cannot be delivered because the transmission line has a failure. PLC enables simplicity because when the transmission line has a failure, this is detected, and the information is not sent erroneously.

F. Transition From the Conventional Grid

The transition to the digital grid can be done gradually, so as to minimize capital expense. Furthermore, it can use existing transmission lines and also achieve higher capacity on those lines. On today's grid, transmission is often designed with redundant lines for robustness, which are then underutilized. The DGR can achieve redundancies through alternate paths between subgrids, and can therefore utilize each individual line to its capacity.

There are several ways to transition from the conventional grid.

When the strategy is to increase grid robustness and energy security, the existing large area synchronous grid can be subdivided into two or three subgrids, with digital grid connections between each subgrid. This improves robustness to wide area failure and prevents sabotage from affecting more than the local subgrid. Segmentation of the wide-area grid so as to improve robustness was recently proposed by Clark *et al.* [35], which states "segmenting the grid . . . into a set of dc-inter-connected sectors . . . completely eliminates the regional stability limitations of ac ties and their inherent power-flow problems."

On the other hand, in cases where increasing penetration of renewables becomes an issue, municipalities or other relatively small areas who wish to become self-sufficient can likewise further subdivide the grid, and rely on infrequent imports and exports of energy to supplement their self-generation. This stage will require the deployment of storage.

At the smallest level of granularity, each home can also become a digital grid cell. Such a digital grid home can take advantage of high power applications and retain safer operation than the existing 120 V system using a DGC controlled battery.

IV. Comparison With Other Concepts

A. Differences Between the Digital Grid and Smart Grids

The smart grid, which is currently being widely developed, is contributing methods to manage power on the grid by computerization, especially by managing the load at the consumer end [36]. Nevertheless, the grid is a synchronous system and the power flow depends on the existing impedance within the grid.

Even if the power flow is intended to be improved through automation [37], the power flow cannot be completely controlled with available data because of the complexity of the fluctuating impedance. Some equipment such as FACTS (flexible ac transmission systems), HVDC (high voltage direct current) [38], EPRI's IntelliGrid [39], or Controllable Network Transformers from the Georgia Institute of Technology [40] are proposed to improve the partial power flow in synchronized system, but not to control power flow asynchronously nor to be coupled with information.

B. Packetized Energy

H. Saito and J. Toyoda introduced the concept of packetized electric power tagged by power routers, which was based on the research of the Open Electric Energy Network in 1995 and 1997 [36], [37]. This research was seminal because it proposed the routing of power with identifying information. However, this concept was made only in regards to the synchronous grid, and does not comprehend asynchronous transmission and arbitrary routing of energy with information.

C. Power Cluster

A power cluster configured through a network of microgrids was also previously conceived. This concept, called "ECO net," which exchanged energy among clusters using a power router, was submitted by Y. Matsumoto and S. Yanabu. The ECO net proposed a new power grid architecture which exchanges energy using power routers among hierarchically organized power clusters. ECO net used dc between clusters, and it can also be said to be seminal [41].

There have been many other proposals such as using routers to control the energy flow and using mesh type networks, however, most of them are more general ideas.

V. Digital Electric Power

Each DGR is configured as one unit integrated with multiple parallel terminals. One CPU controls both power and information, controls each terminal, and controls the set of terminals. The energy and information are integrated into a unit and delivered to the coordinated power line. The basic idea is to integrate the energy and the information into a unit and control it simultaneously, even though an actual system may have multiple CPUs, digital signal processors (DSPs), etc. In this research paper, the energy with information is called "digital electric power."

The standard energy information format has leading header information, main body of energy (payload) and footer information. Both information and power pass through the same power line. Information can be separated into two sets. One is a simple key signal that passes through the same power line and the other contains additional information including the key signal analyzer and passes through an outside data network in advance. Therefore, the bandwidth of this key signal can be relatively small. When using PLC communications, those two sets can be combined into one [26]–[28]. The header has both sender address and receiver address, so the digital electric power can be transferred to the given address passing through the specified intermediate DGRs. The required amount of exchanged energy can be divided into smaller units, where each has its own header

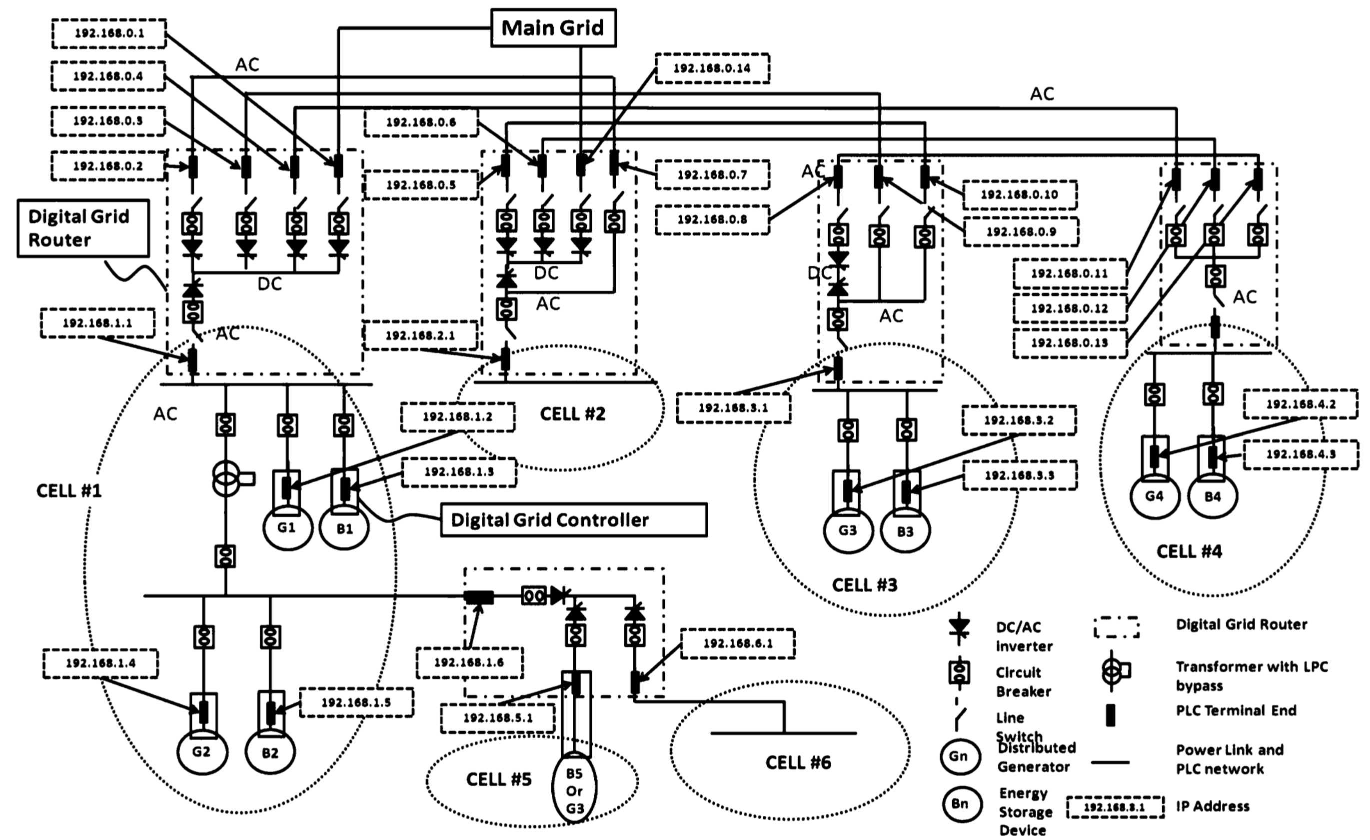

Fig. 8. Example line diagram of the digital grid.

and thereby these subunits of energy can be sent by different routes.

The magnitude of the electric power and its duration can be included in the header information as the energy profile, and the footer information can be used to define the end. This profile can be recorded for energy trading information.

VI. Specific Examples of Digital Grids

Fig. 8 shows the specific example of a digital grid as proposed in this paper. This configuration can be achieved by changing the existing power system gradually, exhibiting the benefit that the system can be deployed without system-wide changes.

The cells numbered #1 to #4 do not need to be synchronized with others. Each cell has a large proportion of renewable energy, and manages the supply-demand balance through distributed fossil fuel generator(s) and energy storage. Each cell has its own power generation and load configuration, and the frequency or phase is allowed to vary from cell to cell. Each cell has its own power bus to which generator (G) and storage (B) are connected. The loads from residences are connected also, although not displayed in the figure. The DGRs are shown surrounded by dash-dot-dash lines. The terminal of each DGR is composed of breakers, line switches, and power inverters. Not shown in the figure, the terminal has an inductor or an isolating transformer. The terminal can be configured either with a power inverter or without the power inverter.

The DGRs installed in cells #1, #2, #3, and #4 can exchange energy via connected power lines.

Cell #5 is an example where the DGR is connected to the stand-alone power equipment directly. This enables control of the charging and discharging of energy storage or output of the power generator. Cell #6 is an example of a cell which is subordinate to Cell #1, where Cell #6 operates at a lower voltage rating.

The DGR terminals rectify the received power to dc, and transmit power by inverting to ac. A dc bus is used as a common bus for all the terminals.

When sending ac power, the voltage, phase, and frequency are synchronized with that of the remote cell to which this DGR terminal is connected. The total power of all inputs and outputs to each DGR is controlled so as to be net zero. The dotted ellipse shows cells which have a traditional interregional synchronized system and are operated in a stand-alone mode. The self-reliant cells have generators, storage and various loads (which are not shown) connected via a circuit breaker to the power bus. Each power device (generator or storage units) has a power controller which controls the input and output of the unit. Each DGC (shown as solid line box) receives and transmits signals over the power line to coordinate with other DGCs and DGRs.

Each DGC has a PLC device (shown as a solid black square) at each terminal, and each terminal has a unique IP address. This example uses IPv4 but can readily be replaced with IPv6 and future derivative protocols. Power equipment can communicate with all other equipment, either within the cell or in other cells, using IP addresses.

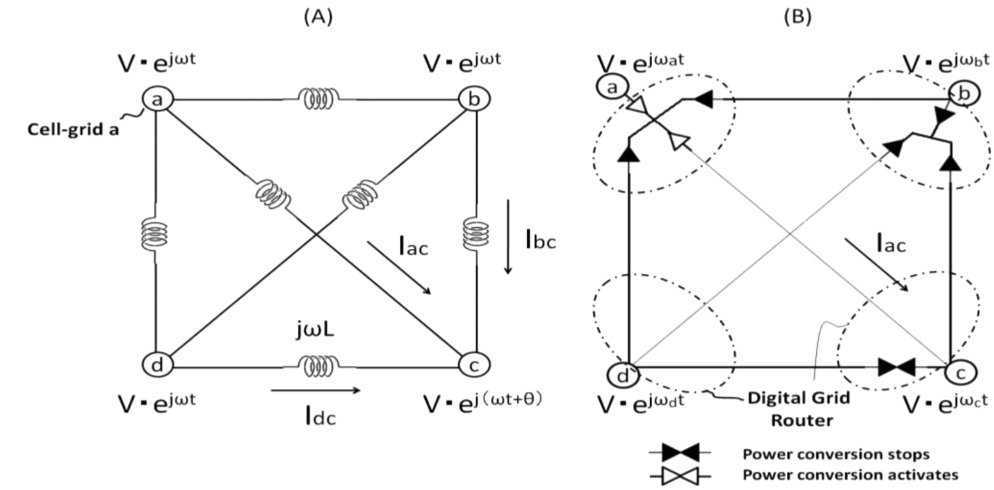

Fig. 9. Power flow in a synchronous grid and a digital grid.

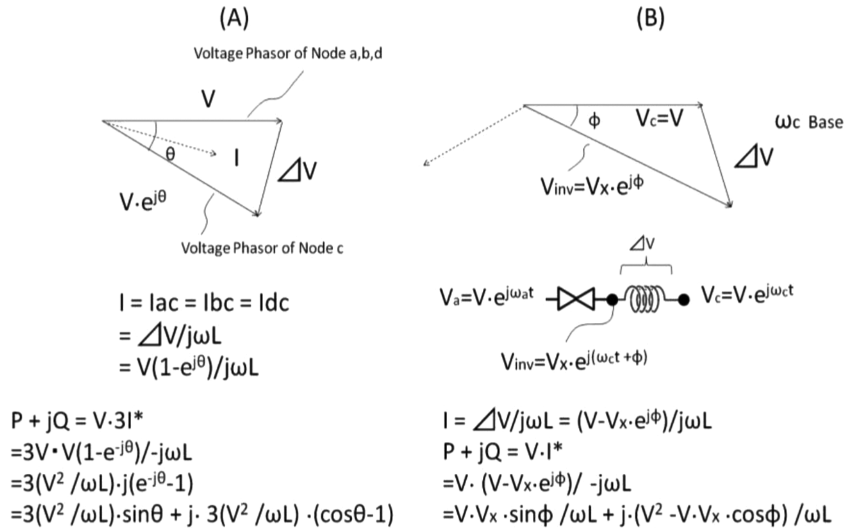

Fig. 10. Calculation of the magnitude of power flow.

VII. DGR AND DGC

A. Digital Grid Router—DGR

A DGR, as shown in Fig. 4, is composed of multiple IP-addressed ac/dc/ac converters with a common dc bus.

Fig. 9 compares power flows in a digital grid with those of an ordinary synchronous grid.

Fig. 9(A) describes four of cell-grids ("a," "b," "c," "d") connected to each other through six transmission lines. If cell grid "c" has phase shift of theta (θ), power flows from neighboring grid "a," "b," and "d." The magnitude of the power depends upon voltage, frequency$(\omega = 2\pi \mathrm{f})$, inductance of power line (L), and theta (θ) as shown in Fig. 10(A). In a real case, these multiple connections should be avoided; otherwise, power flow cannot be controlled.

Fig. 9(B) describes four cell-grids ("a," "b," "c," "d") connected to each other through six transmission lines via DGRs. Each cell-grid can be with different voltages and frequencies (The same voltage "V" is applied in this example.). If the power flow from cell-grid "a" to cell-grid "c" is required, power converters between cell-grids "a" and "c" are operated and the other converters are stopped. The magnitude of power sent depends upon V, $\mathrm{V_x}, \phi, \omega, \mathrm{L}$ as shown in Fig. 10(B). $\mathrm{V_a}$ is converted to dc and inverted to $\mathrm{V_{inv}}(= \mathrm{V_x}\exp(\mathrm{j}(\omega_\mathrm{c}\mathrm{t}+\phi)))$, where $\mathrm{V_x}$ and ϕ are created by PWM conversion as desired to have the same frequency ω_c as in $\mathrm{V_c}$. The magnitude of current "I" is determined by the difference in $\mathrm{V_c}$ and $\mathrm{V_{inv}}$ and phase reactor "L." Thus, $\mathrm{P} = \mathrm{V}\cdot\mathrm{V_x}\sin\phi/\omega\mathrm{L}$ and $\mathrm{Q} = (\mathrm{V}^2 - \mathrm{V}\cdot\mathrm{V_x}\cdot\cos\phi)/\omega\mathrm{L}$ are calculated as shown in Fig. 10(B) and has two degrees of freedom such as $\mathrm{V_x}$ and ϕ, whereas the synchronous power grid, as shown in Fig. 10(A), has zero degrees of freedom.

Therefore, active power and reactive power can be controlled independently. Active power can be pushed into or pulled from each interconnection line as desired within the limit of DGR capacity, unlike in the synchronous grid where load variations across a large area cause complex power flows that are difficult to control. Reactive power can maintain cell voltage as desired within the limits of the DGR capacity. It can also be a voltage source when the grid has to start up after blackout (so-called blackstart).

Multiple BTB components can be used like a DGR; however, DGR uses fewer converters and has the advantage of an integrated system control as is described in this paper.

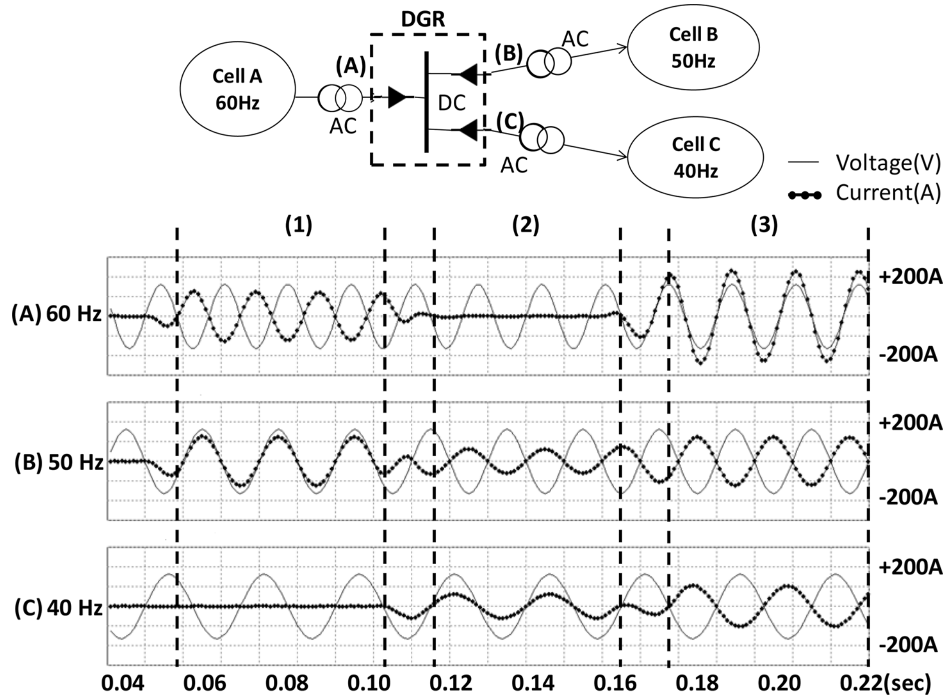

Fig. 11. Transient of power flow among cells using DGR.

Fig. 11 shows a simple simulation of three-way power conversion. The model was developed using power simulation software PSIM.

Cells A, B, and C have different frequencies of 60 Hz, 50 Hz, and 40 Hz respectively. Voltages for those cells are 6.6 kV. DGR legs are connected with each grid via 6.6 kV/200 V transformers. DGR legs are made of IGBTs and operated at 10 kHz PWM. Leg (A) is in master mode which maintains dc bus voltages, whereas legs (B) and (C) are in slave mode which maintains active power flow as desired.

As shown in zone (1), 10 kW is delivered from (A) to (B) and still the voltage waves are kept in sinusoidal form. Current in (C) is zero. In zone (2), 10 kW is delivered from (C) to (B) and the current in (A) becomes zero. In zone (3), 50 kW is taken from (A) and 20 kW is delivered to (B) and 30 kW is delivered to (C), respectively. Total power coming in and going out from DGR is maintained at zero. During transitions in zone (1), (2), and (3), current changes smoothly and voltage waves are kept constant.

If the control signal specifies sending 1 kW for 1 min including an IP address, whatever the magnitude of power and timeframe is, that is a packet of energy, thereby defining the digitalized grid.

As shown in this simulation, it is easy to control power flow among cells with different frequency and phase. When a fault occurs, the DGR can instantly stop the gate signal of the converter which is faster than switchgears. This will stop a cascading blackout. A DGR can also be used in stand-alone cells such as in developing countries.

B. Digital Grid Controller—DGC

The DGC is attached to the controllers of generators and energy storage units within the cell. The DGC communicates with other DGCs and DGRs and dispatches commands to the controllers of generators, loads, and energy storage units. The DGC maintains and can transmit information such as the status of generators, the state of charge (SOC) of energy storage, electric load information, etc.

It is possible to plan and reserve energy exchanges in advance using weather forecasts to predict the fluctuations of power output from wind or solar generators.

VIII. Communications Technology for the Digital Grid

A flexible and low cost communications control system can be developed if it is modeled after the architecture of the Internet and Internet protocols.

Communications technology which is widely deployed for many applications on the Internet, using Internet Protocols (IP) is sufficient for the digital grid. The low cost which this equipment has achieved as well as the advances in technology which will continue to be made can be used to the best advantage for the digital grid.

The technology which can be used includes routing, routing optimization and automatic updating, automated address assignment, packet sequence control, flow control and collision control, and data error detection and correction.

IX. Energy Exchange Procedure on the Digital Grid

A. Energy Exchange Procedure

The following steps describe the general steps of energy exchange.

1) Either the DGR or the DGC broadcasts a request to the other equipment to find a candidate. The broadcast outlines trading conditions including various options such as the

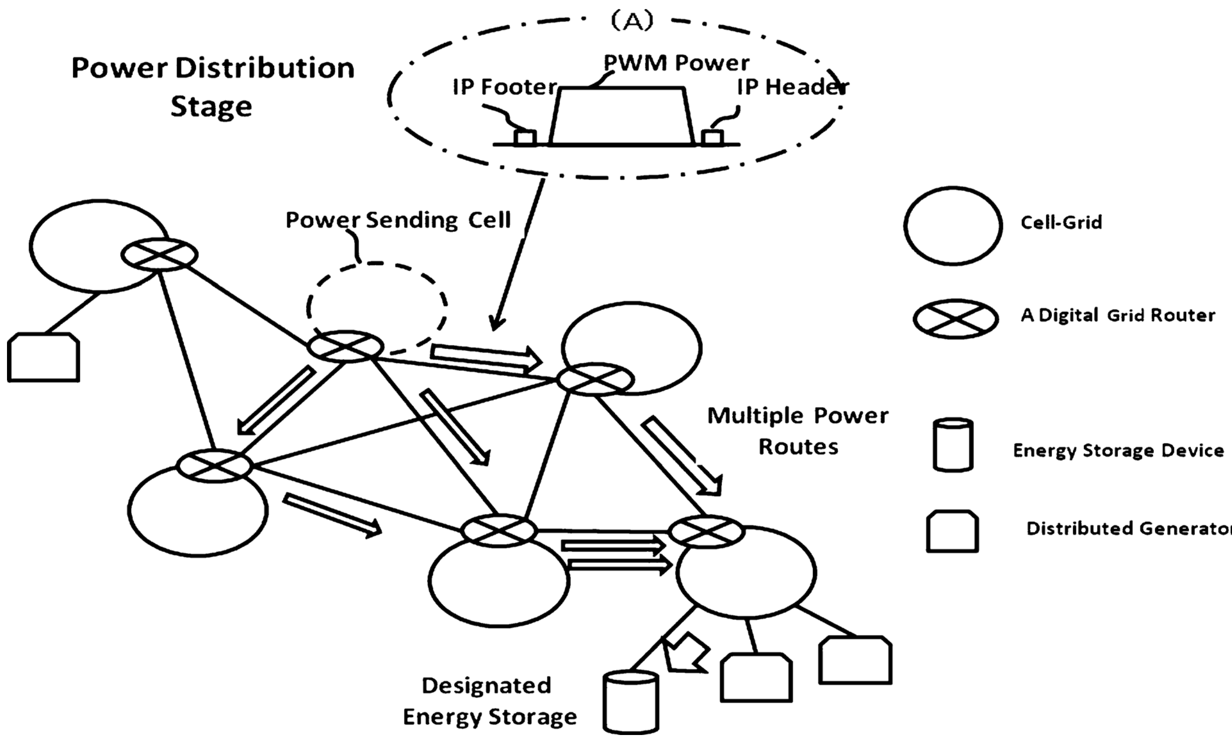

Fig. 12. Energy flow among cells using DGRs.

quantity and direction of real power, the quantity and direction of reactive power, starting time of exchange, ending of exchange, minimum and maximum exchange trading price, and type of power generator. If any power equipment can supply under the requested conditions, then it replies with an offer of trading conditions.

2) Reserve the energy exchange with one candidate, and get an acknowledgement to confirm. Reserved trading conditions are almost the same as those of the request. The system which accepts this reservation replies with a repeat of the suppliers terms to confirm.
3) These processes are similar to the ordinary reservation in hotels, air tickets, etc. The reservation can be for a few seconds or a few days in advance.
4) Find the best route to the candidate from the requester. It is very important to use an algorithm which minimizes power loss due to power conversion and transmission line loss as shown in Fig. 12.

If there are many energy exchange requests, there are several methods to offset and minimize the total power loss. Routing issues can be solved by focusing on the economic efficiency, including price information for lost power, and optimizing based on the physical limitations.

B. Recording Energy Transactions

Energy transactions between DGRs and DGCs are initiated through requests from others.

Each DGR and DGC operates autonomously based on their local policy, algorithms and rules, initiating the power transfers appropriately. Energy flows will be monitored by built-in metering devices and recorded together with reservation information, including time, seller, buyer, price, energy source, energy amount, etc. These records will be like a bankbook for ordinary financial transactions as shown in Table I.

TABLE I
RECORDING ENERGY TRANSACTIONS

Date	Starting Time	Finishing Time	Source Cell	Sending Cell	Receiving Energy	Sending Energy	Loss	Balance	Tariff (c/kWh)	Money Balance
2010.6.25	10:29	11:50	Cell A		200 kWh		10 kWh	190 kWh	30.4	xxx
2010.6.26	12:50	15:40		Cell X		120 kWh	7 kWh	63 kWh	19.5	xxx
2010.6.27	16:40	18:30	Cell B		420 kWh		20 kWh	463 kWh	20.2	xxx
2010.6.28	22:15	0:40		Cell Y		230 kWh	16 kWh	217 kWh	38.5	xxx

The digital grid enables electric energy to be handled as a commodity product, resulting in low, stable prices. This mechanism may create futures and derivatives markets related to weather forecasting. A certification process will be necessary for accounting for the inevitable losses caused by transmission and storage. This function can be provided by a third party energy service provider.

X. CONCLUSION

The digital grid enables a more robust grid, by segmenting it into largely autonomous cells, and with energy storage enables a large proportion of renewable energy, which cannot be achieved with the existing grid architecture. It can be applied to the current grid step by step and may contribute to increase the utilization factor of transmission lines. It also enables the commoditization of energy, resulting in low and stable electricity prices. Finally, it supports new third party services such as energy storage, energy trading markets, green energy supply certification service and emergency energy supply.

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Rikiya Abe (M'08) was born in Fukushima prefecture in Japan on September 12, 1953. He graduated from the Electronics Engineering at the University of Tokyo, Japan. He received a doctoral degree from institutions of chemical engineering at Kyushu University, Japan.

His employment experience included the Electric Power Development Company, Tokyo; Electric Power Research Institute, USA; and the University of Tokyo. He is a Professor since 2008 at the University of Tokyo and is teaching undergraduate students at Program for Social Innovation and graduate students at Technology Management for Innovation. His special fields of interest included renewable energy, energy storage, and smart grid.

Hisao Taoka (M'78–SM'97) was born in Okayama prefecture, Japan, on September 8, 1953. He graduated from the Electric Engineering and the Graduate School of Engineering, University of Tokyo, Japan, in 1977 and 1979, respectively. He received a doctoral degree from the University of Tokyo in 1986.

In 1979, he joined Mitsubishi Electric Corporation, where he has engaged in the research on power system control and analysis using advanced computer technologies. After being a Professor at Fukui University of Technology, Japan, for seven years, he is now an Associate Professor in the Graduate School of Engineering, Electrical and Electronics Engineering, University of Fukui, Japan.

Prof. Taoka is a Member of CIGRE and IEE of Japan.

David McQuilkin (M'05) was born in the United States in 1953. He received the B.S. degree in physics from Wheaton College, Wheaton, IL, in 1975.

His employment experience includes Asia Pacific Ventures, Xerox, and AT&T. He is currently a consulting engineer with Kyumaru Pacific Alliances, Cupertino, CA, providing services to Japanese and U.S.-based companies. His specialties include information technology hardware and software engineering, renewable energy, energy storage, and the smart grid.

Mr. McQuilkin is a Member of the IEEE Power and Energy Society and the Association for Computing Machinery.