Digital Grid: Communicative Electrical Grids of the Future

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***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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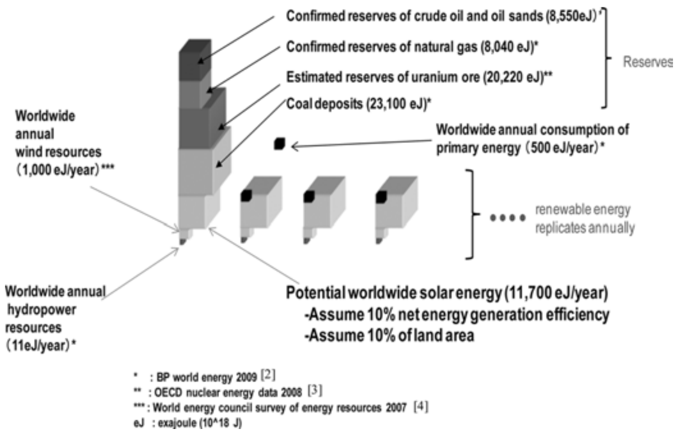

Fig. 1. World energy consumption and energy sources (produced by Rikiya Abe).

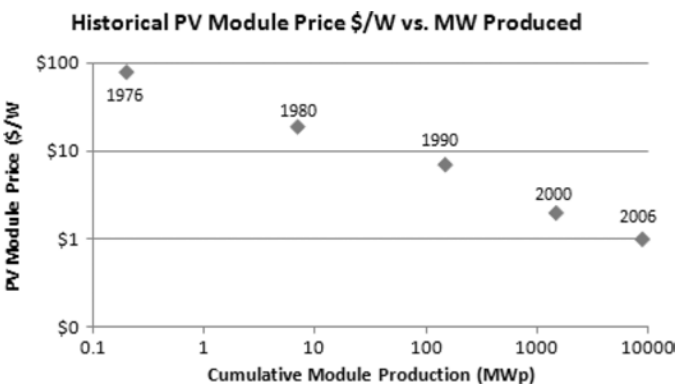

Fig. 2. Historical PV module price versus MW produced [15].

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.

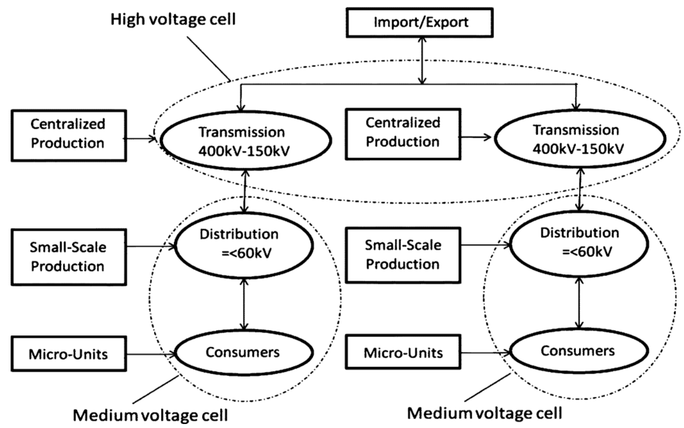

Fig. 3. Cell concept introduced in Denmark [24].

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.