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Smart Grids with Intelligent Periphery: An Architecture for the Energy Internet

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ABSTRACT A future smart grid must fulfill the vision of the Energy Internet in which millions of people produce their own energy from renewables in their homes, offices, and factories and share it with each other. Electric vehicles and local energy storage will be widely deployed. Internet technology will be utilized to transform the power grid into an energy-sharing inter-grid. To prepare for the future, a smart grid with intelligent periphery, or smart GRIP, is proposed. The building blocks of GRIP architecture are called clusters and include an energy-management system (EMS)-controlled transmission grid in the core and distribution grids, micro-grids, and smart buildings and homes on the periphery; all of which are hierarchically structured. The layered architecture of GRIP allows a seamless transition from the present to the future and plug-and-play interoperability. The basic functions of a cluster consist of ① dispatch, ② smoothing, and ③ mitigation. A risk-limiting dispatch methodology is presented; a new device, called the electric spring, is developed for smoothing out fluctuations in periphery clusters; and means to mitigate failures are discussed.

KEYWORDS smart grid, future grid, Energy Internet, energy-management system, integrating renewables, power system operation, power system control, distribution automation systems, demand-side management

1 Introduction

China's rapid transformation in the last 30 years from an underdeveloped country to the second largest economy of the world has lifted hundreds of millions of people out of poverty and brought prosperity to her people and the rest of the world. China's rise has inspired many others to follow. The 21st century will mark the "rise of the rest"—from Asia and South America to Africa. The path of China's development largely follows that of the West: The economic growth is driven by fossil-fuel energy and accompanied by the depletion of resources and degradation of the environment. The damage brought by environmental pollution has started to show up in China as the devastating long-term health and economic consequences of the development. China is the number one emitter of greenhouse gases (primarily carbon dioxide) that contribute to anthropogenic global climate change, a crisis that is leading to an existential threat to human civilization. India is on its way to become the number one greenhouse gas emitter in the next 20 years. The conventional path to economic development is not sustainable and is no longer an option. At the upcoming 2015 Climate Summit in Paris, world leaders are expected to declare Intended Nationally Determined Contributions to reduce greenhouse gas emission. Time is running out. This may be the last chance for humankind to limit global temperature rise to 2 °C above pre-industrial levels—the scientific consensus of the threshold to catastrophic and irreversible damage to the planet. The United Nations has resolved to develop the post-2015 Sustainable Development Goals in order to achieve global economic development without environmental damage (zero poverty/zero carbon).

The electric grid plays a central role in the chain of energy conversion from sources to useful activities that drive economic development. Sustainable development critically relies on a workable future grid to support it. A properly functioning future grid will be able to contribute to ① decarbonization of energy sources, ② efficiency improvement in conversion processes and end-uses, and ③ clean transportation.

- **Decarbonization of energy**: Future energy sources will have to transition from fossil fuels to renewables such as wind and solar power, and perhaps nuclear, in order to reduce carbon emission to the atmosphere. Nuclear generation is an established and often controversial technology whose integration to the grid does not change the status quo. Future grids must be operated in such a way as to facilitate greater extraction and utilization of renewable energy resources, which are intermittent and variable.
- **Efficiency improvement**: Electricity helps to decouple

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energy use from gross domestic product (GDP) and population growth, contributing to reducing carbon intensity (carbon emission per GDP). Future smart grids that apply advanced computer, communication, and Internet technologies will be able to significantly improve efficiency in all aspects of electricity generation, transmission, and utilization processes. End-use energy management helps energy to be used more efficiently through more intelligent management.
- **Clean transportation**: Transportation accounts for a quarter of total carbon emission in the US and other advanced countries—second only to electricity. Electric vehicles, coupled with decarbonized future grids, will help transform the existing transportation modes into clean and sustainable transportation.

Section 2 of this paper discusses what lies ahead in the future grid, or Energy Internet. In order to get a firm "grip" on the future, we propose the development of a smart grid with intelligent periphery, or smart GRIP, for the future. Section 3 lays out a layered architecture for smart GRIP that facilitates a seamless transformation from the present to the future. The building blocks of GRIP are called clusters. The basic functions of all clusters, large or small, are the same, consisting of ① dispatch, ② smoothing, and ③ mitigation. A risk-limiting dispatch methodology is proposed in Section 4 and a new device, called the electric spring, for smoothing out power and voltage fluctuations on the future grid is described in Section 5. Section 6 discusses ways to mitigate failure and concluding remarks are made in Section 7.

2 Future grids: The Energy Internet

The conventional electric grid evolved over the span of the 20th century. This was a different era in which the energy sources were primarily large-scale fossil-fuel power plants, augmented by large hydro and nuclear plants. The technologies for these resources favored economy of scale. A brief summary of the salient features of the conventional electric grid is listed below for later comparison with upcoming transformations.

(1) The suppliers, that is, the power companies, have the obligation to serve random load demands from consumers. In other words, loads are passive and uncontrollable.

(2) In an era of mechanical devices, an economic and reliability trade-off has led to the differences in the structures and operation of the high-voltage transmission grid and the low-voltage distribution grid.

(3) The lack of economically viable energy-storage technology (except for pumped storage where the geography allows it) obligates the system operator to strive for instantaneous power balance. A whole set of planning and operation functions are built around this main objective.

(4) The emergence of the energy-management system (EMS) in the 1970s brought intelligence into the transmission grid [1]. An EMS's real-time monitoring and control may cover several hundred generating and transmission substations using a centralized architecture. The EMS stretched the limit of the capability of the computer and communication technologies at the time.

(5) Uncertainties on the grid are manifested in ① load variations and ② equipment failures. Both can be handled adequately, albeit conservatively, using deterministic methodologies (i.e., reserve margins and N–1 contingencies).

Innovations in the improvement of efficiency and reliability of wind and solar power technologies in recent years are making renewable resources cost-competitive to conventional energy sources for electricity [2]. Megawatt-level on-shore wind turbines have become a mature and standard technology and are lower in levelized overall plant costs without government subsidy in increasingly number of locations. Technologies for offshore wind power are advancing. Solar photovoltaics (PVs) are on a fast track of technological development [3]. Innovations in material science research have led to newer generations of PV cells, such as thin-film, multi-junction, organic, and quantum-dot cells, that promise much higher efficiency and lower cost in the future. Embedded power-electronics enabled power optimizers in PV modules further improve the overall power output and efficiency of the system. The prices of PV modules have reduced to one-fifth and those of PV systems to one-third within the past six years.

Energy-storage technology is the key to the future success of electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs). Grid-connected energy storage is also a valuable component that provides flexibility in instantaneous supply-demand balance in the presence of intermittent and variable renewables. Rapid innovations have greatly changed the performance of several conventional energy-storage technologies and introduced some new and novel ones. Grid-level rechargeable batteries, including lithium-ion, flow, and other types, are steadily overcoming their traditional barriers of small capacity and high cost. Research and development in flywheel, compressed air, thermal (molten salts), and hydrogen storage systems are making great progress. In addition to physical storage devices, great potential lies in the exploitation of end-use side energy storage for the grid. For example, energy-demand management of water heaters and air-conditioning cycling utilizes the thermal energy stored in water tanks and buildings at consumer premises in exchange for electricity. Smart vehicle charging and discharging (or vehicle-to-grid, V2G) technology utilizes electrochemical energy stored in the batteries of EVs/PHEVs to act as energy storage for the grid. These "virtual energy-storage systems," when properly managed in the future grid, can provide a large quantity of cost-efficient power in both directions to the grid.

Since 2010, the world has added more solar PVs than in the previous four decades. Renewable generation led by wind and followed by hydro and solar power accounts for a major share of new generation investment worldwide. Wind and solar power generation in the world today are around 400 GW and 200 GW, respectively. By 2050, according to the International Energy Agency (IEA), wind may supply 30% of global electricity and solar 15%–20% [4]. The IEA's roadmap calls for governments to encourage the supply of half of the vehicle fleet by EVs and PHEVs by 2050 when the grid will