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A hierarchical optimization model for energy data flow in smart grid power systems

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ABSTRACT

Environmental concerns and high prices of fossil fuels increase the feasibility of using renewable energy sources in smart grid. Smart grid technologies are currently being developed to provide efficient and clean power systems. Communication in smart grid allows different components to collaborate and exchange information. Traditionally, the utility company uses a central management unit to schedule energy generation, distribution, and consumption. Using centralized management in a very large scale smart grid forms a single point of failure and leads to serious scalability issues in terms of information delivery and processing. In this paper, a three-level hierarchical optimization approach is proposed to solve scalability, computational overhead, and minimize daily electricity cost through maximizing the used percentage of renewable energy. At level one, a single home or a group of homes are combined to form an optimized power entity (OPE) that satisfies its load demand from its own renewable energy sources (RESs). At level two, a group of OPEs satisfies energy requirements of all OPEs within the group. At level three, excess in renewable energy from different groups along with the energy from the grid is used to fulfill unsatisfied demands and the remaining energy are sent to storage devices.

1. Introduction

Environmental responsibility is one of the main concerns in Academia as well as the industry. Researchers from both sides are collaborating to address environment grand challenges and to accelerate the research in this field [1]. Managing carbon footprint and power consumption [2] are examples of such efforts. The challenges are even greater today. Continuous development in industrial and commercial sectors increases the burdens on the traditional electrical power grid and creates new issues like continuous blackouts and increasing carbon emissions [3]. To solve these issues and many others, communication and information networks have been integrated with the electrical power grid to generate the Smart Grid (SG). Moreover, setting up regulations and standards for deploying smart power systems has taken a great interest in many countries. Smart grid promises to provide benefits such as reliability, efficiency, reduced power loss, distributed power demands over time to vanish peak hours, low billing prices, automated monitoring and control for effective fault tolerance and energy restoration. In addition, smart grid incorporates three main power components: renewable energy (wind and solar photovoltaics (PV)),

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Nomenclature

OO	number of over-generated OPEs
UO	number of under-generated OPEs
OG	number of over-generated groups
UG	number of under-generated groups
$F_{i,j}$	price factor of transmitting energy from OG i to UG j
B	number of batteries in the system or a group
H	number of hydrogen FCs in the system or a group
E^b_{Scap}	maximum storage capacity of battery b
E^b_{Smin}	minimum preferred charge of battery b
E^b_S	amount of energy currently stored in battery b
ce^b, de^b	charge and discharge efficiencies of battery b
cr^b, dr^b	charge and discharge rates of battery b
DoD	depth of discharge of battery b
C	charge mode
E^b_H	amount of energy currently stored in hydrogen storage h
$E^i_{Wx}+E^i_{PVx}$	excess wind and solar energy from OPE i
$E^i_{Wx1}+E^i_{PVx1}$	excess wind and solar energy from OPE i after first step of optimization
$E^g_{Wxg}+E^g_{PVxg}$	excess wind and solar energy from group g after second step of optimization
E^i_{Lx}	unsatisfied load demand of OPE i
E^i_{Lx1}	unsatisfied load demand of OPE i after first step of optimization
E^g_{Lxg}	unsatisfied load demand of group g after second step of optimization
P_W, P_{PV}	price of wind and solar energy
P_S, P_H	price of energy discharged from storage batteries and hydrogen storage
$x^{s,d}$	distance $x^{s,d}$ between energy source s and energy destinations d
$E^{i,j}_W+E^{i,j}_{PV}$	wind and solar energy used by UO j from OO i
$E^{i,j}_{Wg}+E^{i,j}_{PVg}$	wind and solar energy used by UG j from OG i
$E^{b,j}_{Sd}+E^{h,j}_{Hd}$	energy used by under-generated OPE j generated from the discharging of storage batteries b and hydrogen storage h
$E^{g,j}_G$	grid energy used by under-generated OPE j from grid g
$E^{i,b}_{Scw}, E^{i,b}_{Scpv}$	energy charged to battery b from wind and solar energy of OO i
$E^{i,h}_{Shcw}, E^{i,h}_{Shcpv}$	energy charged to hydrogen FC h from wind and solar energy of OO i
E^g_{ex}	total excess energy in group g from RESs after third step of optimization
f^w, f^{pv}	price factor of wind and solar energy
f^s, f^h	price factor of energy discharged from storage batteries and hydrogen storage

electrical vehicles, and storage systems. Some researchers addressed the infrastructure of the smart grid and developed optimality models for energy generation, consumption, and pricing as in [4–6]. Companies like IBM have started to manufacture and release new types of energy meters (smart meters) that report information needed in optimizing techniques [7]. In smart grid, the communication is a two-way communication where energy and data are exchanged between nodes of the power system [8–10]. It is expected to drive machine-to-machine understanding of power aware systems [11]. Mainly, there are three categories of networks in the smart grid infrastructure based on the scope and area of the network which are: Home Area Network (HAN), Neighborhood Area Network (NAN), and Wide Area Network (WAN) [12,13]. Fig. 1 shows a typical smart grid structure with different scopes. Currently and in the future, efficiency in power systems and smart grid is critical. Smart grid can benefit to achieve efficiency from the recent developments in the information technology sector such as mathematical optimization, artificial intelligent, wireless communication, and cyber-security.

Recently many offshore and onshore wind farms have been developed and some are still under construction. The largest offshore wind farm is powering United Kingdom with 300 MW of renewable energy. In Denmark, the offshore wind farm provides the country with 207 MW. In addition, the European Wind Energy association is planning to extend the power generated from wind by investing 194 billion Euros to generate 230 GW of power by 2020. European countries aim to produce 400 GW of power by 2050 from offshore and onshore as well. On the other hand, USA has the largest onshore wind farms named Roscoe 2010 which generates 781.5 MW. Another wind farm under construction in the USA is the Alta Wind Energy Farm that is being developed by Terra-Gen Power. In March 2010, Terra-Gen received a grant of 394 Million US Dollars to build Alta-Oak Mojave project which consists of installing 320 wind turbine generators. The largest proposed onshore project is the Gansu Wind Farm which is to be installed in China with a capacity to generate 10,000 MW. In addition to wind-based power generators, solar photovoltaics (PV) arrays are playing a key role in supplying power demands in many countries with the largest (Sarnia) in Ontario, Canada which was completed in 2011. Sarnia was developed by First Solar and Enbridge incorporation with a capacity of 97 MW. Other projects are the Montalto di Castro that generates a power of 84.2 MW in Italy, and the Solarpark Finsterwalde I,II,III in Germany with a capacity of 80.7 MW. Many others are developing power generation systems using solar PVs such as in Spain and USA.

The technology of smart grid brings many different fields to cooperate to achieve an efficient system. One of these fields is mathematical optimization through the study of wind and PVs profiles in different locations. The objective is to find an optimal solution in utilizing the generated power. The solution needs to incorporate storage sites for any extra power to be used at the times where renewable energy is not sufficient. This is inevitable because the sunlight and wind varies during daytime and the time of the year. Hence, some other forms of energy resources – such as gas, petroleum, hydrogen, biofuels – can be used at low periods to achieve sustainable and reliable energy generation.

Traditionally, a utility company uses a central management unit to find the optimal solution. However, using