Energy 44 (2012) 167–177

Contents lists available at SciVerse ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

A user-mode distributed energy management architecture for smart grid applications

B.B. Alagoz [a,*], A. Kaygusuz [a], A. Karabiber [b]

[a] Inonu University, Electrical-Electronics Engineering, Turkey
[b] Bingol University, Electrical-Electronics Engineering, Turkey

ARTICLE INFO

Article history:
Received 21 February 2012
Received in revised form
8 June 2012
Accepted 8 June 2012
Available online 20 July 2012

Keywords:
Energy balance
Probabilistic analysis for smart grids
Energy reliability and efficiency
Distributed generation
Distributed storage

ABSTRACT

Future smart grids will require a flexible, observable, and controllable network architecture for reliable and efficient energy delivery under uncertain conditions. They will also necessitate variability in distributed energy generators and demand-side loads. This study presents a tree-like user-mode network architecture responding to these requirements. The approaches presented for the next-generation grid architecture facilitate the management of distributed generation strategies based on renewable sources, distributed storage, and demand-side load management.

The authors draw a framework for the future digital power grid concept and assess its viability in relation to volatile, diverse generation and consumption possibilities. In this sense, probabilistic energy balance analyses of tree-like user-mode networks with a stochastic end-user population are conducted to investigate the energy reliability of the proposed grid. A case study based on published generation and consumption profile data is also presented, and several generation scenarios formed by variants of this data are discussed.

1. Introduction

The complexity of the electric power infrastructure continues to grow with increasing load demand [1]. In order to respond to this in an environmentally friendly manner, the integration of distributed renewable energy farms and the utilization of distributed energy storage are becoming major concerns for stakeholders involved in the design of future energy delivery grids. The conventional electric grid model, known as the dump grid, is not versatile enough to properly respond to these expectations [2]. This is because in traditional grids, the power flow is mainly designed to be unidirectional, supporting a continuous flow from power stations to static consumers. In future grids, static consumers will not be desirable; rather, users will be active, and therefore the power flow in grids need to be capable of dynamically switching between the consumer and local renewable energy providers.

This switching in the function of consumers requires a smarter grid infrastructure in order to deal with the dynamic alterations in power flows throughout the network. Unfortunately, the instantaneous flow control and optimization operations are a challenging task for the traditional electric power grid because of the difficulty in obtaining an accurate system representation in real-time [1]. There is therefore a need for more observable, accessible, and controllable network infrastructures. Future grids, also referred as to as smart grids, will include distributed volatile renewable energy sources, domestic energy storage, and uncertain load demands due to the diversity of appliances. The smart grid will have to intelligently and automatically perform control and optimization operations and manage the rapid dynamic reconfiguration of system parameters to handle such distributed and volatile energy and load dispatches [3,4].

Due to increasing energy prices and the greenhouse effect, more efficient electricity production is desirable, preferably based on renewable resources. One of the most striking technologies involves generation methods using such resources, as evident in wind turbine and photovoltaic (PV) parks [4–7]. The use of these technologies, particularly at the domestic level, will greatly reduce energy losses in transport and hence the cost of energy. The applicability of these technologies depends on three main concepts related to future energy delivery and sharing grids: distributed generation (DG), distributed energy storage (DES), and demand-side load management (DSLM).

In DG, energy sources are distributed into the power grid, ranging from the megawatt level to domestic generators at the kilowatt level such as renewable sources, micro-turbines and

* Corresponding author.
E-mail addresses: alagozb@yahoo.com, baykant.alagoz@inonu.edu.tr (B.B. Alagoz).

0360-5442/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.energy.2012.06.051

Nomenclature

W	Potential energy
Q	Amount of charge
V	Voltage
t	Time
N_i^j	Node i in j-order of node hierarchy
T_g	Energy assurance period
Y_i^j	Energy supplement rate for element i in order j
G_i^j	Amount of stored energy by element i in order j
C_i^j	Amount of demanded energy by element i in order j
α_g^j	Energy generation loss rate in the domain of j-order nodes
α_c^j	Energy consumption loss rate in the domain of j-order nodes
G_T^j	Total energy provided by the end users or sub-nodes in node domain j
C_T^j	Total energy consumption by the end users or sub-nodes in node domain j
$W_i^j(t)$	Load profile function of element i in order j
$S_i^j(t)$	Generation profile function of element i in order j
$E[\cdot]$	Expected value
$MoS(\cdot)$	User-mode switching function
ε^j	Total energy balance error of the node-order j
ε	Global energy balance error
ΔE_q^j	Energy requirement of the element q at order j
P_{ES}	Probability of being in ES mode
Mode_i^j	Mode of element i in order j
R_{UMN}	Energy reliability degree in UMN
Y_1^r	Root node
E_{ES}	Average energy generation of end-users
E_{EC}	Average energy consumption of end-users
α_T^n	Overall energy transport loss rate of an n-order energy-balanced network

List of abbreviations

DG	distributed generation
DES	distributed energy storage
DSLM	demand-side load management
ES	energy supplier mode
EC	energy consumer mode
ESR	energy supplement rate
EAP	energy assurance period
PV	Photovoltaic
SCCU	smart-control communication unit
UMN	user-mode network
RB	reliability boundary
EB	maximal efficiency boundary

combined heat and power plants (CHP) [4–17]. In future smart grids, domestic energy generation will play a substantial role in renewable energy generation and energy efficiency [8]. Local energy production, storage, and consumption will greatly reduce transportation loss and complications in global maintenance management, and therefore the cost of energy. In this sense, DG will be the fundamental element of microgrids [14–17], in which energy production, storage, and consumption can be locally carried out in an islanded manner. Future microgrids are expected to operate as a self-supporting energy system (islanded operation), importing only a small amount of electricity from outside of the cluster [4,16], or even exporting their redundant energy production to neighboring clusters.

Energy storage is a key underpinning of the concept of the smart grid, which aims to support sustainable energy provision [18]. Particularly with the growing amount of renewable resources in the electricity supply chain, there is a growing demand for electricity storage [4]. However, large-capacity electricity storage is difficult to implement and leads to high losses; DES implementation is a possible solutions to the problem of the energy storage requirements of the smart grid. Another advantage of DES implementation in a smart grid is that micro-storage (or domestic storage) supports DSLM strategies [19], increasing generation efficiency by enabling peak demand shaving that uses stored energy [14,15]. Domestic energy storage controlled by an intelligent management system can serve to shift the electricity demand away from peak periods. The management of peak demand via intelligent management techniques [18] will make the grid smarter and more energy efficient [19].

Recent efforts of diverse stakeholders to realize smart grids have exhibited the following prioritized trends: reliability, renewable resources, demand-side response, electric storage, and electric transportation [20]. However, a common vision of stakeholders in terms of the interaction of appliances and the management policy of grid resources is needed to facilitate the integration of the evolving smart grid resources.

This paper presents a probabilistic analysis of a reliable, controllable, demand-responsive, balanced energy delivery network architecture for the decentralized hierarchical integration of microgrids; further, this promotes prevailing DG, DES, and DSLM concepts. The grid architecture is defined via appliance interaction and interconnection models. This study focuses on the presentation of a feasible model for the integration and management of evolving smart-grid appliances that is responsive to stakeholders' future grid expectations such as energy reliability, the use of diverse renewable energy resources [21], demand-responsive intelligent management [22,23], and energy-efficient transportation. The decentralized hierarchical architecture of the energy delivery network provides a scalable and flexible interaction between smart grid participants [24–27]. Advantages of decentralized hierarchical architectures were discussed on large-scale distributed systems in data processing [28], distributed control [29,30] and power distribution [24,26]. Future smart grids should be scalable and flexible structure so as to rapidly respond demands of active users, called as prosumers. The traditional, one-way, centralized network architectures are not effective to respond volatile, diverse generation and consumption profiles of active users. In a previous work, a prosumer-based, service-oriented architecture were discussed and remarked that prosumer-based decentralized architectures can serve as platform for the development of a large number of innovative smart grid applications [31]. Katz et al. discussed an information-centric energy infrastructure for the 21st century and they suggested that pervasive information would allow us to use energy more effectively, by agilely dispatching it to where it is needed, integrating intermittent renewable sources and intelligently adapting loads to match the available energy [26].

Energy balance is a main objective when it comes to developing reliable energy grids that exhibit uncertainty and variation in both energy generation [32] and the demand profiles of appliances. The real-time decentralized control of energy flows is necessary to maintain energy balance over the entire network. Reliability and efficiency in energy distribution can be achieved by smartly controlling the flow of energy throughout the network. The modeling of an electrical system that considers the stochastic process and probabilistic factors (social, ecological, physical,