G Model
EPSR-3999; No. of Pages 8
ARTICLE IN PRESS

Electric Power Systems Research xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Electric Power Systems Research

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

Integrated dispatch of generation and load: A pathway towards smart grids

Haiwang Zhong [a,*], Qing Xia [a], Ye Xia [a], Chongqing Kang [a], Le Xie [b], Wen He [c], Huiling Zhang [c]

[a] Department of Electrical Engineering, Tsinghua University, Beijing 100084, China
[b] Department of Electrical and Computer Engineering, Texas A&M University, College Station, TX, USA
[c] State Grid Ningxia Electric Power Company, Yinchuan, Ningxia, China

ARTICLE INFO

Article history:
Received 1 November 2013
Received in revised form 30 March 2014
Accepted 5 April 2014
Available online xxx

Keywords:
Integrated dispatch of generation and load (IDGL)
Load adjustment cost (LAC)
Settlement mechanism
Load shifting
Consumption mode switching

ABSTRACT

With large scale integration of intermittent renewable energy such as wind and solar, it is becoming a challenge to maintain the power balance by purely dispatching generation. Demand-side resources should be utilized to (1) avoid the prohibitive investment in backup generation and (2) *dance* with intermittent renewable generation. To reap the potential benefits from the demand side, we propose a new framework termed integrated dispatch of generation and load (IDGL). In IDGL, the load adjustment cost (LAC) is introduced to express the willingness of customers to change their consumption levels. A formulation of IDGL is proposed in which the customer responses, such as load shifting and consumption mode switching, can be explicitly modeled. We also present a new settlement mechanism in which the load adjustment costs of responsive customers are paid by non-responsive customers. The advantage of this mechanism is that customers are guided to bid according to their real LACs. Case studies based on the IEEE 30-bus system and a real-world power system in China demonstrate the effectiveness and the economic benefits of IDGL.

1. Introduction

In conventional power systems, the generation is run in the "load-following" manner. System operators often focus on the supply side of the power balance equation. The demand side of the equation is often viewed as a constant value in day ahead scheduling processes [1]. The general approach to cope with capacity shortage during peak hours is to invest heavily in building more power plants and transmission facilities [2]. However, the consequence is significant underutilization of peaking units during off-peak hours [1]. The large-scale integration of intermittent renewable generation such as wind and solar also brings great challenges to power grids [3,4]. Provided that wind power is often adversely correlated with system demand patterns, wind curtailment is a big issue in places where wind power penetration is high [5]. Solar generation can change at even a faster time scale in response to the passing clouds [6]. The operating practices in some regions such as ERCOT indicate that balancing power generation and load has already become a challenge for system operators [7]. Therefore, attention is shifting to the demand side of the power balance equation. The demand-side resources, if well utilized, can avoid the requirement for prohibitive investments in backup generation and help to accommodate more intermittent renewable generation [8].

The role of the demand side in grid operations has been evolving. Enabled by smart grid technologies, customers can interact with the generation side via various demand response (DR) programs [9]. It is worth noting that services (such as comfortable room temperature, lighting, cooling and heating) are real customer demands, not electricity *per se*. Hence, a successful DR program should ensure that the services of customers are interrupted as little as possible. To reap the potential benefits from the demand side, the flexibility of customers should be explicitly modeled in system operator dispatch algorithms [10].

In general, the flexibility of customers includes load reduction, load shifting, and consumption mode switching. It should be noted that load shifting only changes the time of day when the load is switched on, while the overall demand of the customer at the end of the day remains the same [11]. A recent study indicates that demand-side management (DSM) programs using load shifting techniques show good potential for reducing the peak loads in power systems [2,10]. Load shifting modeling methods can be

* Corresponding author. Tel.: +86 1062794361.
E-mail address: zhonghw04@gmail.com (H. Zhong).

http://dx.doi.org/10.1016/j.epsr.2014.04.005
0378-7796/© 2014 Elsevier B.V. All rights reserved.

based on demand *elasticity*. The elasticity is a general concept that can be applied to the vast majority of customers. In an electricity market environment where customers are exposed to time-varying electricity prices, customers may want to adjust their power consumption patterns to reduce their electricity purchase costs. The cross-time price elasticity of demand can be used to model the inter-temporal utility of customers [12,13]. A matrix of self- and cross-elasticity is used to model the customer responsive behaviors in [14]. Although elasticity can be easily used to reflect customer responses to changes in prices (such as load reduction and load shifting), to take into account the influence of elasticity, an iterative procedure is often adopted [12]. Oscillations between demand response and prices may occur in this iterative process. In the time-of-use (TOU) environment, the price does not change frequently. Thus, the information exchange between system operators and customer lags and is inadequate. A common price signal is applied to all customers and they respond to the price signal individually. Over-responses and under-responses of customers often occur. Therefore, it is quite difficult for system operators to accurately predict customer responses in advance of the actual operating interval. In the real-time price (RTP) environment, prices vary much more frequently. However, concerns have been raised that RTP may increase the price volatility without proper dispatch models [19]. Another obstacle is that it is quite difficult to obtain the true elasticity of customers in the real world. In addition, the elasticity can only reflect the continuous features of electricity consumption. The discrete features of electricity consumption cannot be rigorously recognized.

Other load shifting modeling methods are based on the physical electricity consumption features of a specific type of customer. Industrial electric heaters, thermal storage, HVACs, pumps, agitators, smelters and refrigerators are modeled as deferrable loads in [10]. The role of load shifting in diminishing the voltage rise effects of distributed generation (DG) has also been investigated in [11]. A real-time demand response model has been proposed for adjusting the hourly load level of a given customer in response to forecasted hourly electricity prices in [15]. The objective is to maximize the customer's utility. The constraints include a minimum daily energy consumption level, maximum/minimum hourly load levels, and ramping limits on the load levels. Plug-in Hybrid Electric Vehicles (PHEV) are also promising flexible customers to improve the grid operation performance [16]. However, the load profile characteristics of customers are usually not explicitly modeled.

The concept of *demand dispatch* was recently proposed in [17]. Demand dispatch aggregates a large number of small loads such as electric vehicles and household appliances via the Internet to help balance generation and load in real time. It is believed that the aggregated demand response can be utilized to support the economical operation of power grids. Demand dispatch is combined with the probabilistic wind power forecasting to help accommodate large shares of wind power in [18]. In places where large portions of electricity are consumed by industrial customers, such as China (approximately 74% of electricity is consumed by large industrial customers), much attention is paid to the demand response from large industrial customers. Most industrial customers are now facing TOU prices in China. Compared with other flexible customers, industrial customers have more constraints on their electricity consumption. For instance, the requirement of continuous electricity service and the energy constraint originates from the order of products. From a psychological perspective, load reduction is undesirable for industrial customers. These customers would rather shift the load from peak hours to off-peak hours. Therefore, in terms of implementation, load shifting is more acceptable for industrial customers. Because the communication and control paths between most wholesale-level customers and the system operator are already in place, in this paper, we will focus on large wholesale-level customers that are directly connected to a network of 110 kV and more.

The major contributions of this paper are summarized as follows:

First, the framework of the integrated dispatch of generation and load (IDGL) is proposed in this paper. In IDGL, loads from large industrial customers are viewed as dispatchable resources, similar to generating units. The system operator can simultaneously optimize both the generation and load to level the system load profile. IDGL can not only integrate more renewable energy, but it can also improve the efficiency of generation. IDGL provides a possible pathway towards smart grids.

Second, the formulation for IDGL is proposed. The customers and generating units are symmetrically modeled. From the perspective of the customers, it is difficult to adjust the electricity consumption interval-by-interval, due to the inter-temporal characteristics of load. In the proposed IDGL model, the physical requirements of individual customers can be rigorously recognized by precisely modeling the load profiles. Therefore, the demand-side resources become more predictable and controllable for system operators. In addition, the generation and demand-side resources can be matched more accurately and efficiently.

Third, the concept of load adjustment cost (LAC) is introduced to express the willingness of customers to change their consumption modes. We design a new settlement mechanism, in which the load adjustment costs of responsive customers are paid by non-responsive customers. The advantage of this mechanism is that customers are guided to bid according to their real load adjustment cost. Under the circumstance of scarce generation capability, if the TOU prices are ineffective to incentivize customers to shift their loads towards off-peak hours, a competition market for load shifting resources can be built based upon the proposed mechanism.

The remainder of this paper is organized as follows. In Section 2, the framework of IDGL is proposed. In Section 3, the mathematical formulation for IDGL is introduced. In Section 4, numerical experiments are conducted based on the IEEE 30-bus system and a real-world power system in China. Section 5 concludes.

2. The framework of the integrated dispatch of generation and load (IDGL)

This section presents the framework for integrated dispatch of generation and load (IDGL), in which the demand and generation side resources are viewed symmetrically. The system operator can simultaneously schedule both the generation and load.

However, the loads of industrial customers are less flexible and less controllable compared with the generating units. Many physical constraints need to be recognized. To simplify implementation, we focus on load shifting and consumption mode switching of industrial customers.

2.1. Load adjustment cost

The responses of industrial customers (such as load shifting and consumption mode switching) changes the lifestyle of workers and requires extra operations that incur extra costs, such as compensation of employees and extra operating costs. To express the costs of customer responses, we introduce a new concept termed the *load adjustment cost* (LAC). The LAC is similar to the startup cost of a