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Game-Theory based dynamic pricing strategies for demand side management in smart grids

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ABSTRACT

With the increasing demand for electricity and the advent of smart grids, developed countries are establishing demand side management (DSM) techniques to influence consumption patterns. The use of dynamic pricing strategies has emerged as a powerful DSM tool to optimize the energy consumption pattern of consumers and simultaneously improve the overall efficacy of the energy market. The main objective of the dynamic pricing strategy is to encourage consumers to participate in peak load reduction and obtain respective incentives in return. In this work, a game theory based dynamic pricing strategy is evaluated for Singapore electricity market, with focus on the residential and commercial sector. The proposed pricing model is tested with five load and price datasets to spread across all possible scenarios including weekdays, weekends, public holidays and the highest/lowest demand in the year. Three pricing strategies are evaluated and compared, namely, the half-hourly Real-Time Pricing (RTP), Time-of-Use (TOU) Pricing and Day-Night (DN) Pricing. The results demonstrate that RTP maximizes peak load reduction for the residential sector and commercial sector by 10% and 5%, respectively. Moreover, the profits are increased by 15.5% and 18.7%, respectively, while total load reduction is minimized to ensure a realistic scenario.

1. Introduction

Electricity has grown to become an essential part of human life. A reliable and seamless supply is required to facilitate economic and industrial growth as well as to improve quality of life. Global electricity demand has been increasing exponentially and is expected to double in value between 2002 and 2030 [1]. Electricity is a non-storable commodity; its wholesale price varies across time periods depending on demands [2]. In most cases however, the consumer is charged a fixed price and the price fluctuations are borne by the utility company. Since consumers are unaffected by wholesale price changes, their demand shows drastic fluctuations with low valleys at night and high peaks during the day. These fluctuations decrease supply reliability, system efficiency and reduce profits for utility companies. Moreover, many countries have also chosen to restructure their power industry and introduce deregulation in their electricity markets. Hence, companies need to establish Demand-Side Management (DSM) strategies to influence user consumption patterns and thereby achieve peak-load reduction. The increasing penetration of renewables and market deregulation has further bolstered the need for operational flexibility in the grid and resulted in development of efficient DSM techniques [3–6]. It is noted that the availability of renewable generation will impact the dynamic pricing strategy and thus, the DSM techniques based on its intermittency and cheaper generation cost.

Demand response techniques can control and modify user consumption patterns through incentive based dynamic pricing techniques. Demand response algorithms have been widely adopted in the literature as they result in significant electricity bill savings and avoid undesirable peaks in the daily load demand, thereby improving the efficiency of the system [7–14]. Today, several developed countries such as USA, Canada and many parts of Europe have successfully developed and implemented dynamic pricing strategies to perform DSM. A 2010 survey conducted by the Federal Energy Regulatory Commission of USA shows that demand response methods could lead to a 7.6% decrease in peak load

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demand and among various time based pricing techniques, TOU pricing is proved to be the most effective [15]. Project Intekellion conducted by the German Government shows that time-variable tariffs for households bring about a 6% energy saving [16].

The electricity demand in Singapore is growing at an annual rate of 5% approximately; 16% of the consumption comes from the residential sector, 38% from the commercial and 46% from industrial sector [17]. Currently, 75% of its market is liberalized and moving towards complete liberalization soon. The residential sector is still considered non-contestable and has a flat pricing of 256.5SGD/MWh throughout the year [18]. The peak period typically occurs at mid-day especially during the afternoons (can be explained by the tropical climate) and non-peak period is seen especially at late night when the consumption is at its lowest. With the increasing standards of living, and the global city status that Singapore now enjoys, it is essential that electricity supply is continuous and seamless. A dynamic pricing strategy is necessary to manage electricity demand and supply patterns as it will help meet user demands, boost profits for generation companies and ensure a reliable supply of electricity at all times of the day.

Dynamic pricing includes techniques such as Real-Time Pricing (RTP), Time-Of-Use pricing (TOU) and Critical-Peak Pricing (CPP). RTP refers to a strategy where prices change for every period of the day: utility companies forecast prices on a day-ahead or hour-ahead basis. TOU pricing divides the day into intervals and charges fixed rates within each interval. These pricing strategies have been studied using different approaches, and tested on academic and practical systems across the world. Yang, Tang and Nehorai proposed an interesting game-theoretic approach for implementing TOU pricing in Ref. [19]. The study uses a multi-stage approach and backward induction to develop a strategy that maximizes profits for both consumers as well as the utility company. In Ref. [20], a RTP based demand response algorithm is proposed to determine the optimal power consumption pattern and pricing, and maximizing the comfort level of the consumers. An equal-incremental cost rule is proposed as a rational solution to determine the electricity pricing in Ref. [21]. It is noted that incremental cost rule refers to a pricing rule which determines the profit maximization based on the incremental cost of power required to satisfy any variation in load demand. The effectiveness of the method was tested with two types of simulated power markets. The price elasticity of the customers was not taken into consideration. A theoretical framework for RTP based on the switched Markov chain model has been developed in Ref. [22]. However most of the above mentioned algorithms and models have been tested using numerical simulations and have not been evaluated using real and practical data sets.

Game Theory has been proven to be an essential tool in capturing the complex and strategic interactions among market participants and for strategic analysis of situations involving multiple independent players. In the previous studies, game theory has been applied to various problems pertaining to electricity markets and demand side management [23,24]. In this work, the main aim is to demonstrate the ability of the proposed game theory based dynamic pricing strategy [19], to implement demand side management, using the real and practical data sets of Singapore. The problem has been formulated based on the modified pricing model to accommodate the Singapore load and market scenario. Moreover, extensive case studies are implemented to evaluate dynamic pricing strategies for Singapore using half-hourly Real-Time Pricing (RTP), Time-of-Use (TOU) Pricing and Day-Night (DN) pricing for residential, commercial and industrial sector (with special focus on the residential and commercial sector). The pricing strategies are tested on practical load and price datasets from Singapore, and all possible scenarios have been considered to accurately measure the robustness of the proposed model. The use of practical data sets of Singapore is essential in the case studies to make the test scenarios more realistic. The results as demonstrated in the 5 case studies for 5 different load and price data sets, including weekdays, weekends, public holidays and the highest/lowest demand in the year, validate the use of proposed dynamic price strategy to encourage the residential and commercial consumers in Singapore to opt for demand side management. It is noted that the data for load demand and market price are taken from Energy Market Company (EMC) of Singapore [18], while the price elasticity of demand (PED) in Singapore is hypothesized from the USA data based on Ameren Illinois studies [19,25–27]. The rest of the paper is organized as follows: Section 2 introduces the proposed pricing model, Section 3 discusses the data collected and methodologies used, Sections 4–6 discuss the results obtained for the residential sector, commercial and industrial sectors respectively and the paper is concluded in Section 7.

2. The proposed pricing model

In this work, a game-theoretic based pricing model is developed to achieve an efficient demand response technique. A multi-stage game approach is adopted to maximize benefits for both consumers and utility companies. The electricity demand, consumption patterns, and Price Elasticity Demand (PED) are observed to vary drastically for different sectors i.e. residential, commercial and industrial sector. Hence, a single-sector approach has been adopted in this work, where-in the sectors are optimized individually to ensure that different strategies could be chosen for different sectors. The pricing model developed in this work defines RTP pricing as well as block pricing.

The utility company aims at maximizing profits while simultaneously adhering to industry regulations and customers' demands. On the contrary, the customers aim at minimizing electricity bills and expect a reliable, uninterrupted power supply. The end result is expected to be a matrix p consisting of electricity sales prices for different sectors over N time intervals. These prices result in reduction of peak load leading to a flattened load curve l.

2.1. Variable and function definitions

2.1.1. Time period (N)

The day is divided into N time intervals to reflect different values for each variable. The subscript k corresponds to a particular period in the day and can take values from 1 to N.

2.1.2. Electricity cost (c_k), price (p_k) and price elasticity of demand (e_k)

The *marginal cost of electricity* "c_k" sis the cost paid by the electricity company and varies depending on the time of day, electricity market and demand.

The *unit sales price of electricity* "p_k" corresponds to the price the utility company will charge its customers and varies depending on the time of the day. This price is fixed by the electricity company and is obtained as a result of the mathematical simulations in this model.

The *fixed price* "n_k" can be interpreted as the price the consumers are currently being charged for the electricity supplied and varies according to the country/sector in picture. Both c_k and n_k are considered as input data for the pricing model developed.

The *short-run price elasticity of demand (PED)* "e_k" is used to represent responsiveness or sensitivity of the quantity demanded to the price change. It essentially provides the percentage change in quantity demanded for every 1% change in price. It helps to