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Residential Demand Response model and impact on voltage profile and losses of an electric distribution network

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ABSTRACT

This paper develops a model for Demand Response (DR) by utilizing consumer behavior modeling considering different scenarios and levels of consumer rationality. Consumer behavior modeling has been done by developing extensive demand-price elasticity matrices for different types of consumers. These price elasticity matrices (PEMs) are utilized to calculate the level of Demand Response for a given consumer considering a day-ahead real time pricing scenario. DR models are applied to the IEEE 8500-node test feeder which is a real world large radial distribution network. A comprehensive analysis has been performed on the effects of demand reduction and redistribution on system voltages and losses. Results show that considerable DR can boost in system voltage due for further demand curtailment through demand side management techniques like Volt/Var Control (VVC).

1. Introduction

The evolution of the deregulation trend in power market has led to the division of integrated power system into individual fields: generation, transmission and distribution. The deregulation has created a healthy competition in the distribution market among distribution companies (Discos). In this process Discos are in need of innovative Smart Grid strategies to realize cost efficiency. Some of these as described by Smart Grid requirements [1] are as follows:

1. Deployment and integration of DR, demand side resources and energy efficiency resources.
2. Deployment of smart technologies for metering, communications concerning grid operations/status and distribution automation.
3. Adoption of Demand Side Management (DSM) techniques like Volt/Var control, voltage reduction, etc.

Both DR and distribution voltage reduction are crucial DSM events that have the common objective of peak demand reduction. Effective peak load shaving is possible by the combined effect of bus voltage reduction, demand reduction and demand re-distribution over time. This paper aims at exploring the possible role of DR as a parameter for Volt/Var Control (VVC) for best possible results of load reduction to achieve energy efficiency and mutual profit for utility and consumers. Residential DR has an equally good potential as industrial DR in mitigating congestion in the network during peak hours. However, establishing DR contracts with residential consumers requires proper modeling of consumption patterns which is far more complicated and random as compared to that of industrial consumers. This could be achieved by load serving entities (LSEs) or DR aggregators (these entities are also being named as DR contractors or simply aggregators). LSEs can represent residential consumers and sign DR contracts with the utility for volume of DR that can be achieved. For the successful implementation of such residential DR contracts, LSEs need comprehensive DR models and thus a study of consumer behavioral patterns. This paper uses elaborate demand-price elasticity matrices (PEMs) to model consumer behavior.

Many previous works have focused on developing different kinds of DR models. Ref. [2] provides substantial literature on fundamental principles on spot pricing of electricity and economic analysis of spot pricing. Significant contribution towards consumer behavior modeling in the form of price elasticity matrices (PEMs) has been done in [3–5]. Other papers in literature are focused on the application of DR from a Smart Grid perspective. A generation scheduling program was developed using elasticity of DR to compute the real time market clearing price of electricity in [6]. Optimal Power Flow for nodal reliability of a system was performed using DR application in [7]. A wholesale bidding mechanism

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involving ISO, utility and the consumer was proposed in [8] that uses consumer modeling through PEMs. Load models were developed in [9] using customer benefit function and PEMs and the resultant models were used in a real world distribution system to show results of load reduction. All these papers make standard assumptions of demand-price elasticity with respect to consumer behavior modeling. However, these assumptions need vital refinement for a better understanding of electricity consumption patterns. A considerable work has been done on Volt/Var control [10] that provides basic guidelines required for optimal voltage control in the low voltage distribution side. Ref. [11] proposes a novel concept of considering DR as a parameter for applying Volt/Var control on a real time basis to realize the maximum potential of both these DSM measures. In this work, PEMs have been developed to accurately model consumer behavior. DR patterns for different consumer types have been derived from these PEMs and integrated into distribution power flow to study the resulting system voltages and losses. Further, a path has been laid to coordinate DR with Volt/Var control that would yield better results of demand curtailment, especially during peak hours.

This paper is organized into seven sections. Section 2 briefly describes DR and its types. Section 3 gives an insight on PEMs and describes the modeling of DR using PEMs. In Section 4 PEM prototypes have been developed assuming different rationality levels of consumers. Section 5 briefly describes the test distribution system and various test scenarios built. Section 6 discusses the voltage and loss analyses performed on the test system. Section 7 draws conclusions and provides the scope for future work.

2. Demand Response and types

US Department of Energy (DOE) defines Demand Response as: changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized. DR is divided into two basic categories and several subgroups.

2.1. Incentive-based programs

1. Direct Load Control (DLC)
2. Interruptible/Curtailable service (I/C)
3. Demand Bidding/Buy Back
4. Emergency Demand Response Program (EDRP)
5. Capacity Market Program (CAP)
6. Ancillary Service Markets (A/S)

2.2. Time-based programs

1. Time-of-Use (TOU) program
2. Real Time Pricing (RTP) program
3. Critical Peak Pricing (CPP) Program

The incentive based DR programs are usually more suited for industrial consumers. Incentive based DR contracts normally exist between the distribution utility and a set of large consumers and most of these schemes involve curtailing the load by consumers for a specified period of time and by a specified level of energy to reduce congestion in the network. However, time based DRs are more suited for residential consumers. In these schemes the day is usually divided into a number of blocks that have different prices of electricity that reflect the true market price for generation of electricity. In case of real time pricing, the day would be usually divided into a number of time slots, for example 24- one hour slots and each slot has a different price for electricity that reflects the real market clearing price. RTP scheme engages maximum customer participation. Communicating real time prices to consumers and expecting them to respond would be cumbersome for both consumers and utility. So recently, utilities have laid down the day-ahead real time pricing scheme wherein the next day's predicted real time prices would be sent to the customers before hand and they would be billed for their consumption based on this day-ahead price. Time of use pricing is more or less similar to real time pricing, but with a fewer number of time slots to cut down the complexity involved with real time pricing. Critical peak pricing has fixed rate tariff for most part of the day, however it imposes huge pricing for consumption of electricity during a few pre specified hours of the day. For DR to be implemented through a variable tariff scheme (such as real time pricing or time of use pricing) Advanced Metering Infrastructure (AMI) needs to be enabled at the customer side. In this work, day-ahead real time pricing scheme has been considered for developing the DR model.

3. Modeling of Demand Response – price elasticity matrix

By far, PEM has been the most powerful and feasible way of modeling consumer behavior for DR. Considerable literature is already available on the economic principles of DR and basics of PEM. As a prologue to the next section, some aspects of PEM have been described here. Considering electricity as any other commodity, electricity demand does change with price. The demand price elasticity can be defined by the following equation:

$$E = \frac{\Delta d/d_0}{\Delta p/p_0} \tag{1}$$

where Δd and Δp are the changes in demand and price respectively and d_0 and p_0 are the base demand and price respectively.

The whole concept of PEM revolves around the above equation. Elasticity is composed of two different coefficients namely self elasticity (or own-price elasticity) and cross elasticity. Self elasticity (Eq. (2)) is defined as the change in demand at a time instant 't_i' due to change in price at the same time instant 't_i'. Since change in price will have an inverse effect on change in demand, self elasticity takes a negative value. Also there is a cross-time effect involved in the time varying demand-price elasticity. Cross elasticity (Eq. (3)) is defined as the change in demand at time instant 't_i' due to change in price at some other time instant 't_j'. Cross elasticity will be either positive or zero depending on whether the customer is willing to shift the load or not.

$$E(i,i) = \frac{\Delta d(t_i)/d_0}{\Delta p(t_i)/p_0} \tag{2}$$

$$E(i,j) = \frac{\Delta d(t_i)/d_0}{\Delta p(t_j)/p_0} \tag{3}$$

Self elasticity is a measure of load curtailment by the consumer where as cross elasticity is a measure of load shifting. Both these constituents put together make the concept of DR.

For a RTP scenario that has hourly varying rates, PEM will be of the order 24×24. The diagonal elements of the PEM represent self elasticity coefficients and the off-diagonal elements represent cross elasticity coefficients. Each column of a PEM represents the scheduling of loads throughout the day, owing to the change in price at the time instant corresponding to the column number. The overall change in load at time 't_i' due to change in price throughout the day can be obtained by summing up the entire row corresponding to 't_i' as shown in the following equation:

$$\Delta d(t_i) = \sum_{j=1}^{24} E(i,j) * (\Delta p_j/p_0) * d_0 \tag{4}$$