This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

A Human Expert-Based Approach to Electrical Peak Demand Management

D. Bian, *Student Member, IEEE*, M. Pipattanasomporn, *Senior Member, IEEE*, and Saifur. Rahman, *Fellow, IEEE*

***Abstract*—The objective of this paper is to propose a human expert-based approach to electrical peak demand management. The proposed approach helps to allocate demand curtailments (MW) among distribution substations (DS) or feeders in an electric utility service area based on requirements of the central load dispatch center. Demand curtailment allocation is quantified by taking into account demand response (DR) potential and load curtailment priority of each DS, which can be determined using DS loading level, capacity of each DS, customer types (residential/commercial), and load categories (deployable, interruptible, or critical). The analytic hierarchy process is used to model a complex decision-making process according to both expert inputs and objective parameters. Simulation case studies are conducted to demonstrate how the proposed approach can be implemented to perform DR using real-world data from an electric utility. Simulation results demonstrate that the proposed approach is capable of achieving realistic demand curtailment allocations among different DSs to meet the peak load reduction requirements at the utility level.**

***Index Terms*—Demand response (DR), demand curtailment allocation, expert-based and analytic hierarchy process (AHP).**

I. Introduction

IN ORDER to keep the balance between generation and electrical demand during peak hours, electric utilities usually turn on expensive peaking generation units, or buy high-cost electricity at the power pool level. Among the many methods in use today to reduce the peak demand, demand response (DR) is considered as one of the most promising ones. This is because DR can be used as an effective means to curtail or shift loads to alleviate grid stress conditions.

Applying DR to help utilities keep the generation-load balance effectively relies on two major steps. First, the system-level load curtailment amount (MW) needs to be determined. Then, this load curtailment amount needs to be allocated among distribution substations (DSs) or feeders within the utility service area. The total amount of central demand curtailment (MW) can be estimated from the total available generation and forecasted electricity demand in the service area. However, the distribution of this curtailment among DSs is a complex problem. It needs to involve both expert opinions (i.e., importance of customers in different time periods) and objective parameters of DSs (i.e., loading ratio, capacity, and amount of interruptible, deferrable, and critical loads).

The objective of this paper is to introduce an expert-based demand curtailment allocation approach using the analytic hierarchy process (AHP) method. The proposed method can be used to determine appropriate load curtailment amounts (MW) for different DSs. This is based on DSs' loading condition, load classification, customer type, and their importance.

In recent years, many electric utilities in the U.S. have introduced various types of DR programs—mostly direct load control and dynamic pricing. Siemens has introduced its DR approach called surgical demand response (surgical DR). Different from traditional DR, the surgical DR is flexible in load aggregation, which can be defined by the substation, feeder line, zip code, map interface, or several other associations [1]. Caiso implements Day-Of DR programs which are initiated by DR providers and are triggered based on various conditions, such as forecasted temperature, day-ahead forecasted demand, and high-price forecasts [2]. Economic DR, a price-based DR, is introduced by PJM [3]. In addition to the real-world DR implementation, advances in this field can be seen in many publications. In [4] and [5], the authors introduce DR to alleviate the stress condition of electric power systems brought about by EV charging. In [6], DR is used to manage the variability of renewable energy sources. The authors in [7] and [8] mention implementation of DR to shave the peak demand to reduce electric bills. In [9] and [10], DR is considered as interruptible loads to improve the security of the grid. DR can also be used as system reserves for ancillary services [11]–[14]. The authors in [15] examine the automation of residential loads for participation in DR.

As this review suggests, most previous work has focused on DR programs that are implemented at the end-use customer level. However, the approach in this paper focuses on demand curtailment allocation (MW) among different DSs or feeders in a service area. This demand curtailment algorithm involves expert-based input and objective parameters of DSs.

AHP and principal components analysis (PCA) are commonly used multicriteria decision-making techniques [16]. However, the primary difference is: PCA reduces the number of principal components by orthogonal transformation [17], while AHP uses orthogonal transformation to judge the related weights of principal components. The authors in [18] present a unified PQ index using AHP, which can provide an overall assessment of distribution system performance. In [19], the authors use AHP to determine the values of reactive power in

Manuscript received January 14, 2014; revised April 07, 2014, June 12, 2014, and July 15, 2014; accepted August 11, 2014. Paper no. TPWRD-00046-2014.

The authors are with the Electrical and Computer Engineering Department and Advanced Research Institute, Virginia Polytechnic Institute and State University, Arlington, VA 22203 USA (e-mail: desong85@vt.edu; mpipatta@vt.edu; srahman@vt.edu).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TPWRD.2014.2348495

an electric power system based on voltage sensitivity, voltage adequacy, and voltage stability. The AHP method is also used to evaluate the power system's failure rate and PQ [20], [21]. In [22], AHP is used to help decision-making about remote-controllable switch allocation. In [23], the AHP method is used for assessing equipment health for substation maintenance and upgrade planning. The authors in [24] introduce a new short-term load forecasting technique using pairwise comparisons. It is apparent that AHP has not been used for decision making related to DR implementation.

In this paper, an expert-based demand curtailment allocation approach using the AHP method is introduced. Based on opinions from experts, the proposed approach allows an electric utility to prioritize and allocate their demand curtailment at the distribution substation based on the importance of customers and types of loads. To allow DR implementation using the proposed approach, a home/building energy-management (HEM/BEM) system can be implemented to enable automated DR features. With an HEM or a boundary element method (BEM) system, loads can be shed/deferred according to their priority based on customer preferences. This paper assumes ideal transmission and distribution systems by neglecting losses and transmission congestion.

II. Algorithm for DR Allocation

A. Definition of Customer Type and Load Classification

1) Customer Type: Different types of customers usually have different load patterns which makes the customer type a very important factor. In general, customers are classified into the following major categories based on their load patterns: residential, industrial, offices, education, mercantile (e.g., shopping malls and small retails), food (e.g., restaurants, grocery stores), 24 h operation (e.g., health-care centers, police stations, and fire departments) and others. This paper considers residential and commercial (especially office buildings) customers for DR allocation because of the following reasons: 1) These customers have higher flexibility to adjust their loads in response to curtailment requests and 2) consumption patterns of these two load types can be easily distinguished from each other. This enables effective analysis of simulation results. If a finer classification of load types is desired, that can easily be done using the same process mentioned here.

Note that each customer may have onsite distributed energy sources, including renewable energy sources and energy storage. Such energy sources could be used to partially or fully meet the curtailment request. The analysis presented in this paper can also be applied to a stand-alone microgrid [25], which may be stressed due to high load and limited supply.

2) Load Classification: This paper categorizes residential/commercial loads into deferrable, interruptible, and critical loads as follows.

- *Deferrable loads* are those that can be deferred from peak hours and can be deployed any time during off-peak hours.
- *Interruptible loads* are those that can be interrupted momentarily. Load compensation may be necessary as soon as a DR event ends.

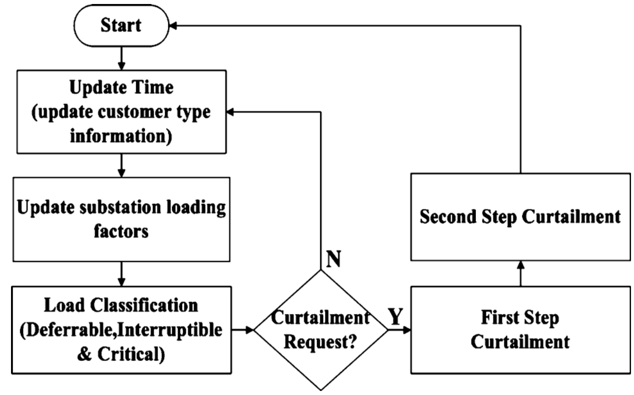


Fig. 1. Flowchart of the proposed DR algorithm.

- *Critical loads* are those that are nondeferrable and noninterruptible.

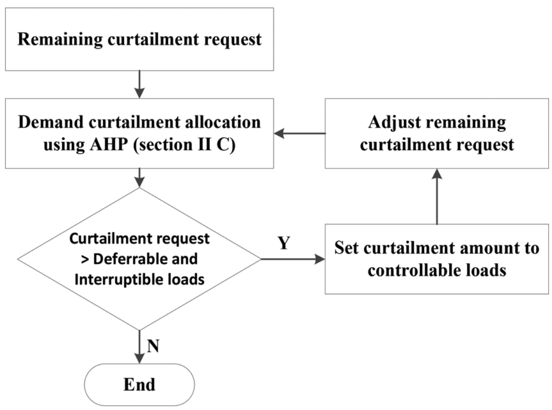
For residential customers, power-intensive electrical loads in the home are air conditioners (AC), water heaters, clothes dryers, and electric vehicles (EV). EVs and clothes dryers are considered as deferrable loads; ac and water heaters are classified as interruptible loads, and all others are critical loads. In this paper, major loads in typical commercial buildings include: cooling, ventilation, lighting, and other loads (e.g., computers, printers, etc.). For this customer type, cooling loads are considered interruptible; and all others (ventilation, lighting, and others) are considered critical. There is no deferrable load in this case.

B. Demand Curtailment Allocation Algorithm

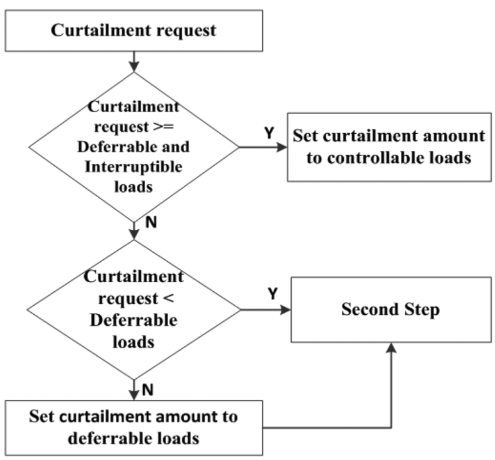
The flowchart of the proposed algorithm is shown in Fig. 1. The proposed algorithm starts by updating information at each DS every fixed time interval (e.g., 15 min). The information to be updated includes: DS capacity, load (MW) by category (i.e., residential/commercial), load (MW) by classification (i.e., deferrable/interruptible/critical), and forecasted loading level of each DS. It is assumed that a demand curtailment request (MW) is sent from an ISO/RTO and crosschecked. Once a curtailment request is received, the first-step curtailment process as shown in Fig. 2(a) is initiated.

The process starts by comparing the requested demand curtailment amount (MW) with the total amount of all deferrable and interruptible loads in the curtailment-requested service area, which can span multiple DSs. If the requested amount is equal or larger than the sum of deferrable and interruptible loads, all deferrable and interruptible loads will be curtailed first, and the balance will come from demand response at the customer level.

The second-step curtailment process as shown in Fig. 2(b) will be initiated: 1) to manage the remaining curtailment requested amount or 2) to manage the original curtailment requested amount that is less than deferrable loads. This step is to allocate the (remaining) requested demand curtailment amount among different DSs based on their curtailment priority factor, which is determined using the three-level AHP as discussed in the next section. Outcomes of AHP are curtailment allocation to each DS in the same service area. According to Fig. 2(b), if the curtailment amount allocated to a particular DS is larger than its



(a)



(b)

Fig. 2. (a) First-step curtailment. (b) Second-step curtailment.

sum of deferrable and interruptible loads, the curtailment contribution of that particular DS will be set equal to its sum of deferrable and interruptible loads; and the remaining amount will be reallocated to other DSs.

C. Determination of Curtailment Priority Factor Using AHP

In this paper, a three-level AHP method is proposed to rank the curtailment priority of each DS, and determine the curtailment allocation to each DS. The structure of AHP is shown in Fig. 3. Decision criteria have three levels as explained below.

The 1st-level criteria involve three different groups of experts' judgments, representing the weight of their opinions. The experts in this paper: customer relations department, system operators/dispatchers, and utility commission staff. Note that in using the AHP method, relative importance—as given by various experts—is used as opposed to their absolute judgments. Thus, the unlikely offscale remark by one expert will not skew results.

The 2nd-level criteria are criteria related to each DS, including DS loading condition, load classification, and customer-type factor (CTF).

The 3rd-level criteria expand the aforementionmed criteria as follows:

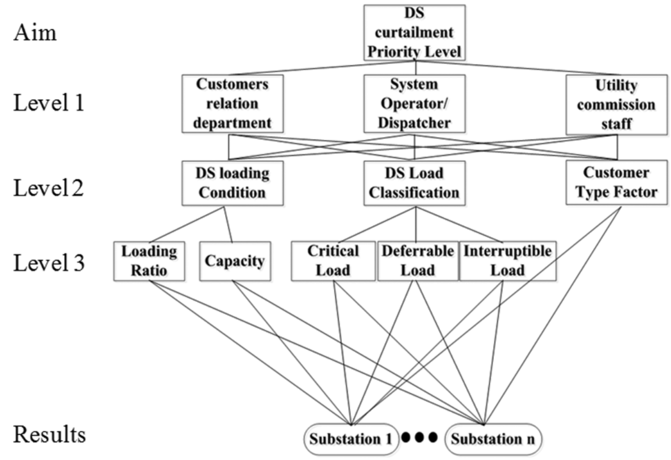


Fig. 3. Three-level AHP structure.

i) DS loading condition includes the DS loading ratio and its capacity. The DS loading ratio is calculated by

$$\text{DS loading ratio} = \frac{\text{DS load (MW)}}{\text{DS capacity (MW)}}. \qquad (1)$$

ii) DS load classification is as explained in Section II-B, including deferrable, interruptible, and critical loads. To determine DS load-by-load classification, (2)–(4) show how to calculate the amount of deferrable, interruptible, and critical loads in every time step, respectively

$$\text{Deferrable load} = \sum (L_{\text{it}} * \text{DP}_{\text{it}}) \quad (i = 1, 2) \qquad (2)$$

$$\text{Interruptible load} = \sum (L_{it} * \text{IP}_{\text{it}}) \quad (i = 1, 2) \qquad (3)$$

$$\text{Critical load} = \sum (L_{it} * \text{CP}_{\text{it}}) \quad (i = 1, 2) \qquad (4)$$

where

L_{it}	total load (MW) of customer type i, time t;
DP_{it}	deferrable load percentage;
IP_{it}	interruptible load percentage;
CP_{it}	critical load percentage;
i	1—residential customers; 2—commercial customers.

iii) CTF is used to present the importance of DS's customers in different time periods. DS's CTF is determined using

$$\text{DS customer type factor} = \sum\nolimits_{i=1}^{2} (P_{\text{it}} * I_{\text{it}}) \qquad (5)$$

where

P_{it}	load percentage of customer i in time interval t;
I_{it}	important level of customer i in time interval t;
i:	1—residential customers; 2—commercial customers.

The important level (I_{it}) is further explained in Section III-C.

1) DS Curtailment Priority Factor: The DS curtailment priority factor is determined using (6), where W is DS criteria weight (a $1 \times n$ matrix, n is the number of criteria being considered); and F is the DS criteria factor (an $m \times n$ matrix, m is the number of DSs). The method to determine W and F are explained

$$\text{DS curtailment priority factor} = [W_{1 \times xn}] * [F_{m*n}]^T. \quad (6)$$

2) DS Criteria Weights (W): DS criteria weights (W) are used to show the importance levels of criteria. In this case, W is a matrix of size 1×6, representing six criteria, namely (i.e., loading ratio, DS capacity, critical load, deferrable load, interruptible load, and CTF). This can be obtained by calculating the weights of each level of criteria in AHP (Fig. 3) according to the following steps [16]: First, a pairwise comparison matrix is generated for each criterion based on Saaty's levels [26]. For example, 1 as equal importance; 3 as moderate importance of one over another; 5 as essential or strong importance; 7 as demonstrated importance; and 9 as extreme importance; and 2,4,6,8 are intermediate values between the two adjacent judgments. Second, a pair-wise comparison table is created and a judgment matrix J is derived for each criterion. Third, the Eigenvector corresponding to the maximum Eigenvalue of J is calculated. This Eigenvector reflects priority levels of elements in matrix J [26]. Finally, Eigenvectors are normalized by making the sum of all normalized Eigenvectors equal to 1.

The normalized Eigenvector for the 1st-level criteria directly serves as the weight for each criterion i in level one ($W_{1i} = [W_{11}, W_{12}, W_{13}]$). Then, weight for each criterion j in level two ($W_{2j} = [W_{21}, W_{22}, W_{23}]$) can be obtained by multiplying the level-1 weight (W_{1i}) with the normalized Eigenvector associated with each criterion j in level two with respect to criterion i in level one (A_{ij}). See the following equation:

$$W_{2j} = \text{normalized}(W_{1i} * A_{ij}). \quad (7)$$

By repeating the aforementioned steps for each level, the overall weight matrix can be obtained. This is the DS criteria weight (W).

3) DS Criteria Factors (F): To calculate F, a table with actual data of all six criteria of each DS (i.e., loading ratio, DS capacity, critical load, deferrable load, interruptible load, and CTF) must be obtained. For each criterion, a pair-wise comparison matrix is created. The Eigenvectors are calculated; and the resulting normalized Eigenvectors associated with the maximum Eigenvalue are taken as DS criteria factors for that particular criterion. Repeat the aforementioned steps to obtain DS criteria factors (F) for the rest of the criteria in order. By combining all DS criteria factors for all six criteria, the resulting matrix F of size 5×6 can be obtained.

III. Case Study

A. Description of Distribution Substations

In this study, it is assumed that a utility has its total loads in the area served by five DSs. The capacity and number of residential and commercial customers served by each DS is summarized in Table I.

TABLE I
DISTRIBUTION SUBSTATION DATA

DS	Capacity (MW)	No. of Residential Customers	No. of Commercial Customers
1	252	18,698	1,206
2	262	20,132	1,294
3	271	21,499	1,377
4	280	22,873	1,461
5	290	24,336	1,550

TABLE II
DS LOAD BY CUSTOMER TYPE AT 15:00

DS	Total Load at 15:00	Residential load (MW)	Residential load (%)	Commercial load (MW)	Commercial load (%)
1	197.50	34.44	17.44	163.06	82.56
2	175.91	37.09	21.08	138.83	78.92
3	153.24	39.60	25.84	113.64	74.16
4	130.30	42.13	32.33	88.17	67.67
5	107.47	44.83	41.71	62.65	58.29

The data used in this case study are derived from distribution feeders in a service area of an electric utility in Virginia. The data are available every 15-minute intervals, and the day selected for the case study is a hot summer day in August. Table II shows an example of DSs' load (MW) by customer type at 15:00.

B. Calculation of DS Criteria Weight (W)

In order to calculate DS criteria weight, the following pairwise comparison matrices are constructed based on a survey. The method was introduced in Section II-C-2.

- L_{11} represents pairwise comparison matrix of level-1 criteria, i.e., the level of relative importance of customer's, utility's and policy maker's opinions. In this case study, L_{11} implies that the customer's opinion is considered as the most important (marked as 5). This is followed by the policy maker's opinion (marked as 3) and the utility's opinion (marked as 1). The Eigenvector corresponding to the maximum Eigenvalue of L_{11} are [0.92; 0.15; 0.37]

$$L_{11} = \begin{bmatrix} 1 & 5 & 3 \\ \frac{1}{5} & 1 & \frac{1}{3} \\ \frac{1}{3} & 3 & 1 \end{bmatrix}. \quad (8)$$

- L_{21}, L_{22} and L_{23} are pairwise comparison matrices of level-2 criteria, which show customer's, utility's and policy maker's opinions respectively about the importance of DS loading condition, as compared to DS load classification and CTF. The Eigenvectors corresponding to the maximum Eigenvalues are [0.1; 0.39; 0.91], [0.92; 0.14; 0.36], [0.15; 0.37; 0.92]

$$L_{21} = \begin{bmatrix} 1 & \frac{1}{5} & \frac{1}{7} \\ 5 & 1 & \frac{1}{3} \\ 7 & 3 & 1 \end{bmatrix} L_{22} = \begin{bmatrix} 1 & 5 & 3 \\ \frac{1}{5} & 1 & \frac{1}{4} \\ \frac{1}{7} & 4 & 1 \end{bmatrix}$$
$$L_{23} = \begin{bmatrix} 1 & \frac{1}{3} & \frac{1}{5} \\ 3 & 1 & \frac{1}{3} \\ 5 & 3 & 1 \end{bmatrix}. \quad (9)$$

- L_{31} and L_{32} show the importance of DS loading ratio, as compared to DS capacity; and that of deferrable load, as compared to interruptible and critical loads, respectively.

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

TABLE III
DS CRITERIA WEIGHT (W)

	Loading Ratio	Capacity	Deferrable	Interruptible	Critical	CTF
Weight	0.1822	0.0911	0.1270	0.0635	0.0212	0.5150

TABLE IV
DS LOADING CONDITION AND LOAD CLASSIFICATION AT 15:00

DS	Load (MW)	Capacity (MW)	Loading ratio	Deferrable (MW)	Interruptible (MW)	Critical (MW)
1	197.50	252	0.7837	1.95	58.70	136.85
2	175.91	262	0.6714	2.10	52.02	121.79
3	153.24	271	0.5655	2.24	45.01	105.99
4	130.30	280	0.4654	2.39	37.93	89.99
5	107.47	290	0.3706	2.54	30.87	74.06

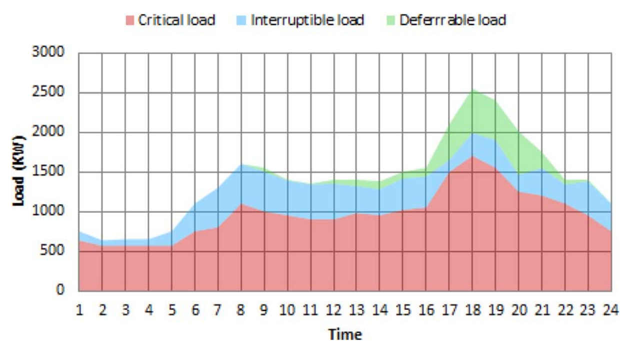


Fig. 4. Load classification for 1000 residential houses in a 24-h period.

The Eigenvectors corresponding to the maximum Eigenvalues are [0.89; 0.45], [0.94; 0.31; 0.16].

$$L_{31} = \begin{bmatrix} 1 & 2 \\ \frac{1}{2} & 1 \end{bmatrix} \quad L_{32} = \begin{bmatrix} 1 & 3 & 6 \\ \frac{1}{3} & 1 & 2 \\ \frac{1}{6} & \frac{1}{2} & 1 \end{bmatrix}. \tag{10}$$

Based on the steps described in Section II-C, and (7), the weights of each level can be calculated. The overall DS criteria weights are shown in Table III.

C. Calculation of DS Criteria Factor (F)

To calculate DS criteria factor (F), the DS loading ratio, capacity, 3-level loads, and CTF are needed.

1) Determination of Loading Ratio: An example of DS loading ratio at 15:00 as shown in Table IV is calculated based on information from Tables I and II using (1).

2) Determination of Load Classification: Load classification at 15:00 (also shown in Table IV) is calculated based on (2)–(4).

Load percentage by classification $(\mathrm{DP}_{it}, \mathrm{IP}_{it}, \mathrm{CP}_{it})$ for residential and commercial customers by can be calculated from Figs. 4 and 5, respectively.

Fig. 4 shows load classification (deferrable/interruptible/critical) for 1000 residential houses with 20% electric vehicle penetration on a summer day, generated based on the Monte Carlo simulation method presented in [27]. Simulated data are used in this case study mainly because data of household load profiles by load type is not easily obtainable in the literature; and the model in [27] has been validated with real-world data from an

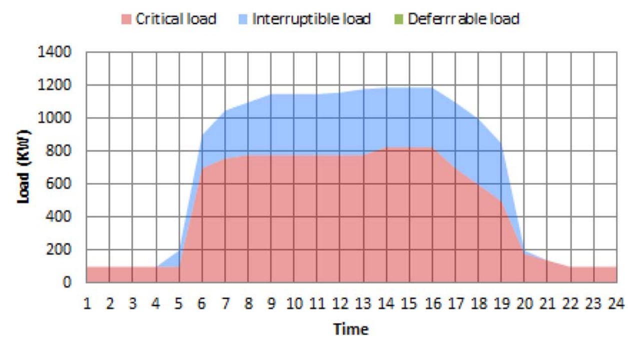


Fig. 5. Load classification for a typical office building in a 24-h period.

electric utility. For example, at 15:00, the three types of loads are 85.5 kW, 394.5 kW and 1020 kW; the percentages of all three types of loads are 5.7%, 26.3% and 68.0%.

Fig. 5 shows load classification in a typical office building on a summer day [28]. For example, at 15:00, the three types of loads are 0 kW, 362 kW and 828 kW the percentages of all three types of loads are 0%, 30.4% and 69.6%.

3) Determination of the CTF: This factor presents the DS importance level. The larger this factor implies, the more important the DS is, and its load curtailment is deferred until the end. CTF is calculated using (5). The load percentage of customer i $(P_{i,t})$ is shown in Table II. Important level of customer i $(I_{i,t})$ is calculated as follows.

Step 1) In this study, a day is divided into six periods (0:00–6:00, 6:00–9:00, 9:00–11:00, 11:00–13:00, 13:00–17:00, and 17:00–24:00) to represent different activities of different types of customers [e.g., office, residential, and food (sales and services)].

Step 2) Create the pair-wise comparison matrix to compare the importance of different customer types. Customer type has been discussed in Section II(A)(1). Table V shows an example of a pair-wise comparison matrix for the 13:00–17:00 period. As shown, during business hours, residential is less important than 24-h operation, mercantile, industry, office, and education. Twenty-four operation (health care/safety department) is always the most important customer type.

Step 3) Calculate Eigenvalues of the pair-wise comparison matrix of interest; select the maximum Eigenvalue; calculate a group of Eigenvectors corresponding to the maximum Eigenvalue; and normalize the Eigenvectors. For the pair-wise comparison matrix as shown in Table V, the maximum Eigenvalue is 7.1143; the corresponding normalized Eigenvectors are shown in the fifth column in Table VI. For each period, Steps 2) and 3) are repeated; and the overall customer-type importance factors are shown in Table VI.

Since commercial (mainly office buildings) and residential customers are the only two customer types in the service area of interest, the importance level of customer i from Table VI

TABLE V
PAIR-WISE COMPARISONS MATRIX FOR THE 13:00–17:00 PERIOD

13:00-17:00	24-hr operation	Food	Residential	Mercantile	Industry	Office	Education
24-hr operation*	1	5	5	5	3	3	3
Food	1/5	1	1	1	1/3	1/3	1/3
Residential	1/5	1	1	1/2	1/3	1/3	1/3
Mercantile	1/5	1	2	1	1/3	1/3	1/3
Industry	1/3	3	3	3	1	1	1
Office	1/3	3	3	3	1	1	1
Education	1/3	3	3	3	1	1	1

* Healthcare/safety department

TABLE VI
IMPORTANT LEVEL OF CUSTOMER I ($I_{I,T}$)

Customer i	Time Period					
	0-6	6-9	9-11	11-13	13-17	17-24
24hr operation	0.3557	0.3491	0.3437	0.3360	0.3666	0.3440
Food	0.1131	0.1636	0.0465	0.1388	0.0560	0.1540
Residential	0.2072	0.1636	0.0526	0.0544	0.0515	0.1540
Mercantile	0.0243	0.1636	0.0916	0.0544	0.0632	0.1540
Industry	0.1560	0.0773	0.1555	0.1388	0.1542	0.0902
Office	0.0718	0.0495	0.1555	0.1388	0.1542	0.0519
Education	0.0718	0.0332	0.1555	0.1388	0.1542	0.0519

TABLE VII
ADJUSTED IMPORTANT LEVEL OF CUSTOMER I (II,T)

Customer i	Time Period					
	0-6	6-9	9-11	11-13	13-17	17-24
Residential	0.7427	0.7676	0.2526	0.2818	0.2504	0.7478
Office	0.2573	0.2324	0.7474	0.7182	0.7496	0.2522

TABLE VIII
DS CUSTOMER-TYPE FACTOR (CTF) AT 15:00

	DS1	DS2	DS3	DS4	DS5
CTF	0.6625	0.6444	0.6206	0.5882	0.5414

TABLE IX
DS CRITERIA DATA AT 15:00

DS	Loading Ratio	Capacity (MW)	Deferrable load (MW)	Interruptible load (MW)	Critical load (MW)	CTF
1	0.7837	252	1.95	58.70	136.85	0.6625
2	0.6714	262	2.10	52.02	121.79	0.6444
3	0.5654	271	2.24	45.01	105.99	0.6206
4	0.4654	280	2.39	37.93	89.99	0.5882
5	0.3706	290	2.54	30.87	74.06	0.5414

is adjusted by scaling up the rate between commercial and residential customers and the sum of their importance levels factors should be equal to one. Repeating the adjustment for each time period, the adjusted results are shown in Table VII. The result is reasonable since office building loads are more important than residential loads during business hours (09:00–17:00); and vice-versa.

Using (5) and the data in Tables II and VII, the DS CTF factor is shown in Table VIII.

DS criteria data are summarized in Table IX, based on information in Tables IV and VIII.

TABLE X
DS CRITERIA FACTORS (F) AT 15:00

DS	Loading Ratio	Capacity	Deferrable load	Interruptible load	Critical load	CTF
1	0.4185	0.0618	0.0618	0.5128	0.0333	0.0403
2	0.2625	0.0973	0.0973	0.2615	0.0634	0.0593
3	0.1599	0.1599	0.1599	0.1290	0.1290	0.1264
4	0.0973	0.2625	0.2625	0.0634	0.2615	0.2602
5	0.0618	0.4185	0.4185	0.0333	0.5128	0.5138

TABLE XI
DS CURTAILMENT PRIORITY FACTOR AT 15:00

DS	Curtailment priority factor	Rank
1	0.1438	3
2	0.1175	5
3	0.1400	4
4	0.2186	2
5	0.3801	1

The steps described in Section II-C are followed to determine the DS criteria factor (F), the result of which is shown in Table X.

D. Determination of the DS Curtailment Priority Factor

The DS curtailment priority factor presents the ranking of DS when facing load curtailment requests. All deferrable and interruptible loads of DSs with a higher curtailment priority factor will be curtailed prior to those of DSs with a lower curtailment priority factor.

The DS criteria weight (W) and DS criteria factor (F) are calculated as explained in Sections III-B and C. Using data from Tables III and X, and (6), the DS curtailment priority factor is shown in Table XI.

From Table XI, it is easy to tell that DS 5 makes the largest contribution when a demand curtailment request is received. This result is reasonable since DS 5 has the most residential customers who are less important than commercial customers during business hours. Though DS 1 has the least number of residential customers, its highest loading ratio increases its priority factor.

IV. RESULTS AND DISCUSSION

This section presents cases when a curtailment is requested in a single time slot, that is, at 15:00; and when curtailment request is imposed for an extended period of time, that is, from 14:00 to 19:00. Note that the paper assumes that each customer unit is equipped with an HEM or a BEM system that enables automated DR functions. This makes the response time almost immediate.

A. Curtailment Request at 15:00

Assuming that the curtailment request is required to be initiated in a service area which contains five DSs at 15:00; and the curtailment amount is assumed to vary from 5% to 25% of the total load of all DSs. Fig. 6 shows that with different amounts of load curtailment request, five DSs made different percentages of contribution.

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

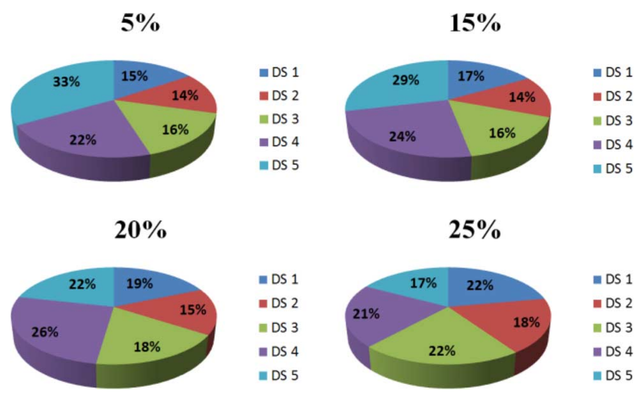


Fig. 6. Percentage of contribution to selected curtailment requests (5%, 15%, 20%, and 25% of the total load) by different DSs.

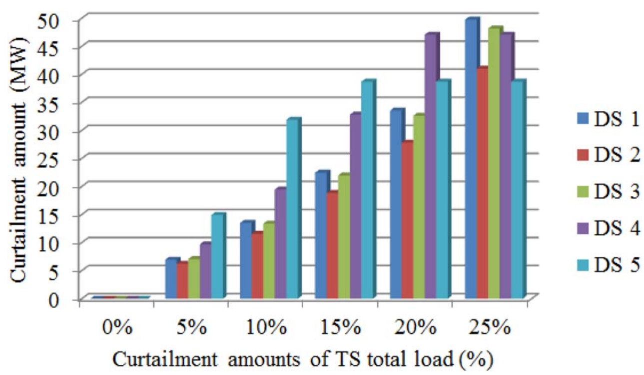


Fig. 7. DS curtailment amount (MW) at 15:00.

Fig. 7 shows the curtailment amount (MW) at 15:00 from each DS. Note that the AHP-based demand curtailment allocation approach presented in this paper curtails only deferrable or interruptible loads. Critical loads are not curtailed. In cases with 5% and 10% curtailment requests, no curtailment request is larger than the sum of deferrable and interruptible loads of any DSs. As a result, DS 5 contains the most residential loads (See Table II), which are less important than commercial loads at 15:00 (See Table VII), making the highest load curtailment contribution. The results are deemed correct.

When a curtailment request is higher than the total amount of deferrable and interruptible load of a DS, only this amount of loads will be curtailed. This is considered as the curtailment limit of a DS. Then, the remaining request will be re-allocated to other DSs. In this case, as DS 5 reaches its curtailment limit at 15% curtailment request, its curtailment contribution remains the same in all higher curtailment requests (e.g., 20% and 25%). The remaining amount is then re-allocated to other four DSs. Since DS 4 holds the second rank in the DS curtailment priority factor (Table XI), it makes the highest load curtailment contribution of the remaining request. At the 20% curtailment request, DS 4 also reaches its curtailment limit and all deferrable and interruptible loads are curtailed. In this case, the other DSs assume the remaining curtailment.

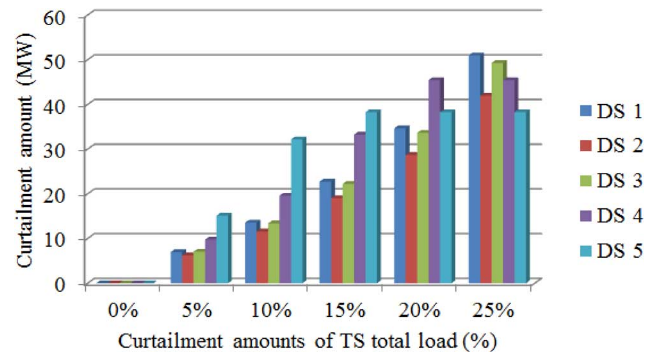


Fig. 8. DS curtailment amount (MW) at 14:15.

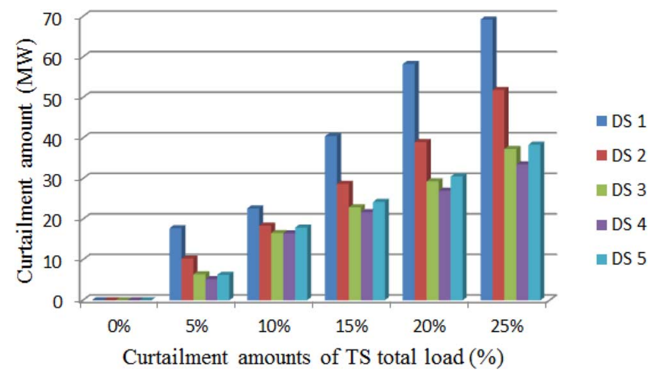


Fig. 9. DS curtailment amount (MW) at 17:15.

B. Curtailment Request From 14:00 to 19:00

In the previous case, the proposed DR allocation algorithm is evaluated in a single time slot. In this case, the curtailment request lasts from 14:00 to 19:00. The curtailment request is assumed to be varied from 5% to 25% of the total load of all DSs (step size is 5%). The demand curtailment allocation is performed in 15-min intervals based on current load monitoring frequency in many U.S. electric utilities for the purpose of determining demand charge. This duration can be adjusted based on real-world DR implementation if necessary.

1) Comparison of Demand Curtailment Allocation During Business and Nonbusiness Hours: Simulation results at 14:15 and 17:15 are shown in Figs. 8 and 9, respectively. In each figure, the x-axis shows a different percentage of curtailment requests. The y-axis shows the curtailment amount (MW) from each DS.

When the curtailment request is less than or equal to DSs' curtailment limits, DS 5 makes the highest contribution to the curtailment request among all DSs (e.g., 5% and 10% curtailment requests at 14:15 as shown in Fig. 8). This is because DS 5 has the highest residential loads (see Table II), and residential loads are less important than commercial loads during business hours (see Table VII). During nonbusiness hours, that is, at 17:15, the contribution from DS 1 is the highest. The result is reasonable since it has the highest commercial load and loading ratio. Once a curtailment request is larger than the curtailment limit of a particular DS, that is, 15%–25%, the curtailment contribution from that DS is set equal to its curtailment limit. And the remaining curtailment request is reallocated among other DSs.

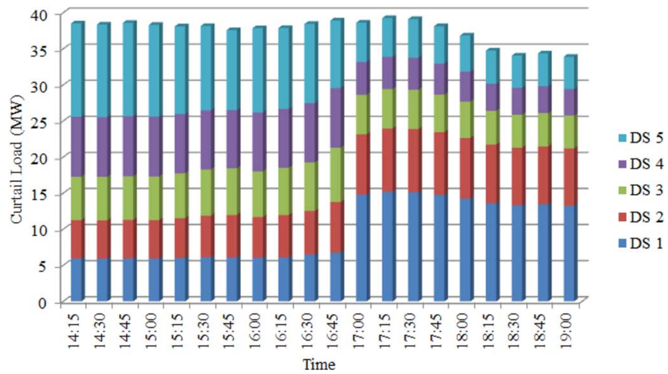


Fig. 10. DS curtailment amount (MW) at 5% curtailment request.

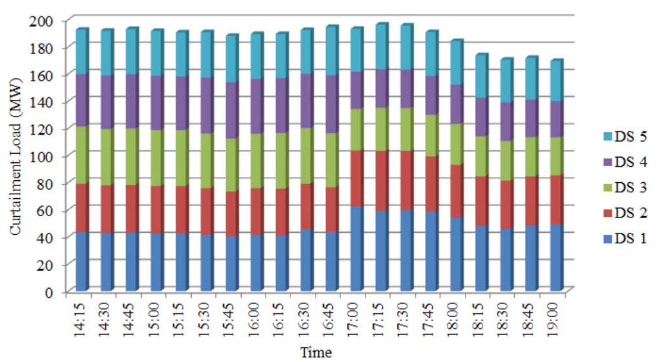


Fig. 11. DS curtailment amount (MW) at 25% curtailment request.

2) Demand Curtailment Allocation With Different Curtailment Request Amounts From 14:00 to 19:00: Simulation results at 5% and 25% curtailment requests are representative and shown in Figs. 10 and 11, respectively.

At low curtailment requests (e.g., 5% as shown in Fig. 10), the results indicate that the curtailment amount of DS 5 is reduced during nonbusiness hours compared to that during business hours, while the curtailment amount of DS 1 increases. This is mainly because of the customer type served by DSs (see Table II). The breakpoint is at 17:00 when changing from business hours to nonbusiness hours.

When curtailment requests reach curtailment limits of any DS: For example, at the 25% curtailment request, DS 5 reaches its curtailment limit from 14:00 to 19:00, which is shown in Fig. 11; thus, its curtailment contribution remains comparable from 14:00 to 19:00.

V. Conclusion

This paper introduces a novel expert-based approach using the AHP method for demand curtailment allocation, which can be beneficial for a utility to prioritize their demand curtailment allocations in its service area. The proposed approach takes into account the DR potential (according to different load classifications) and load curtailment priority (using an AHP method) of each distribution substation (DS). AHP criteria contain the DS loading ratio, DS capacity, load type (deferrable, interruptible and critical), and customer type (residential and commercial). Results of the case studies verify that the proposed DR approach can handle different amounts of load curtailment requests, while satisfying the objective and subjective requirements using the AHP technique.

References

[1] Siemens, Demand response management system: Surgical demand response for a smarter grid, Aug. 2013. [Online]. Available: http://w3.usa.siemens.com/smartgrid/us/en/distributech/Documents/Demand_Response_Distributech.pdf

[2] *"DRAFT Demand Response Participation in MRTU Release i: CAISO Demand Response Resource User Guide,"* ver. 3.0, CAISO, Nov. 2007. [Online]. Available: http://www.caiso.com/Documents/DemandResponseResource-Release1UserGuideVersion3_0.pdf

[3] PJM, "Retail electricity consumer opportunities for demand response in pjm's wholesale markets," Aug. 2013. [Online]. Available: http://www.pjm.com/~/media/markets-ops/dsr/end-use-customer-fact-sheet.ashx

[4] S. Shao, M. Pipattanasomporn, and S. Rahman, "Grid integration of electric vehicles and demand response with customer choice," *IEEE Trans. Smart Grid*, vol. 3, no. 1, pp. 543–550, Mar. 2012.

[5] S. Shao, M. Pipattanasomporn, and S. Rahman, "Demand response as a load shaping tool in an intelligent grid with electric vehicles," *IEEE Trans. Smart Grid*, vol. 2, no. 4, pp. 624–631, Dec. 2011.

[6] H. Wu, M. Shahidehpour, and A. Al-Abdulwahab, "Hourly demand response in day-ahead scheduling for managing the variability of renewable energy," *IET Gen. Transm. Distrib.*, vol. 7, no. 3, pp. 226–234, Mar. 2013.

[7] E. L. Koch, "Automated demand response—From peak shaving to ancillary services," *Proc. IEEE Power Energy Soc. Innovat. Smart Grid Technol.*, pp. 16–20, Jan. 2012.

[8] H. S. V. S. Kumar Nunna and S. Doolla, "Energy management in microgrids using demand response and distributed storage—A multiagent approach," *IEEE Trans. Power Del.*, vol. 28, no. 2, pp. 939–947, Apr. 2013.

[9] S. Huang, J. Dumas, C. Gonzalez-Perez, and W. Lee, "Grid security through load reduction in the ERCOT market," *IEEE Trans. Ind. Appl.*, vol. 45, no. 2, pp. 555–559, Mar. 2009.

[10] Y. Wang, I. R. Pordanjani, and W. Xu, "An event-driven demand response scheme for power system security enhancement," *IEEE Trans. Smart Grid*, vol. 2, no. 1, pp. 23–29, Mar. 2011.

[11] K. Y. Huang and Y. C. Huang, "Integrating direct load control with interruptible load management to provide instantaneous reserves for ancillary services," *IEEE Trans. Power Syst.*, vol. 19, no. 3, pp. 1626–1634, Aug. 2004.

[12] O. E. Moya, "A spinning reserve, load shedding, and economic dispatch solution by bender's decomposition," *IEEE Trans. Power Syst.*, vol. 20, no. 1, pp. 384–388, Feb. 2005.

[13] M. Behrangrad, H. Sugihara, and T. Funaki, "Optimal spinning reserve procurement using demand response in simultaneous clearing process," in *Proc. IEEE Power Energy Soc./Ind. Appl. Soc. Conf. Sustain. Alternative Energy*, Sep. 2009, pp. 28–30.

[14] M. A. Ortega-Vazquez and D. S. Kirschen, "Optimizing the spinning reserve requirements using a cost/benefit analysis," *IEEE Trans. Power Syst.*, vol. 22, no. 1, pp. 24–33, Feb. 2007.

[15] A. Deese, B. Carrigan, E. Stein, and E. Klein, "Automation of residential load in power distribution systems with focus on demand response," *IET Gen., Transm. Distrib.*, vol. 7, pp. 357–365, Jul. 2013.

[16] T. L. Saaty, "Part one: The analytic hierarchy process," in *The Analytic Hierarchy Process*, 1st ed. New York, USA: McGraw-Hill, 1980.

[17] I. T. Jolliffe, "Part 7: Principal component analysis and factor analysis," in *Principal Component Analysis*, 2nd ed. New York, USA: Springer, 2002.

[18] B. Lee, K. M. Kim, and Y. Goh, "Unified power quality index using ideal AHP," in *Proc. 13th Int. Conf. Harmon. Qual. Power*, 2008, pp. 1–5.

[19] S. Fattahi, S. Afsharnia, and M. H. Javidi, "A new AHP-based reactive power valuation method," in *Proc. IEEE Canada Elect. Power Conf.*, 2008, pp. 1–7.

[20] Y. Sun, P. Wang, L. Cheng, and H. Liu, "Operational reliability assessment of power systems considering condition-dependent failure rate," *IET Gen., Transm. Distrib.*, vol. 4, no. 1, pp. 60–72, Jan. 2010.

[21] A. Salarvand, B. Mirzaeian, and M. Moallem, "Obtaining a quantitative index for power quality evaluation in competitive electricity market," *IET Gen., Transm. Distrib.*, vol. 4, no. 7, pp. 810–823, Jan. 2010.

[22] D. P. Bernardon, M. Sperandio, V. J. Garcia, L. N. Canha, A. R. Abaide, and E. F. B. Daza, "AHP decision-making algorithm to allocate remotely controlled switches in distribution networks," *IEEE Trans. Power Del.*, vol. 26, no. 3, pp. 1884–1892, Jul. 2011.

[23] H. Tanaka, S. Tsukao, D. Yamashita, T. Niimura, and R. Yokoyama, "Multiple criteria assessment of substation conditions by pair-wise comparison of analytic hierarchy process," *IEEE Trans. Power Del.*, vol. 25, no. 4, pp. 3017–3023, Oct. 2010.

[24] S. Rahman and G. Shrestha, "A priority vector based technique for load forecasting," *IEEE Trans. Power Syst.*, vol. 6, no. 4, pp. 1459–1465, Nov. 1991.

[25] N. Hatziargyriou, H. Asano, R. Iravani, and C. Marnay, "An overview of ongoing research, development and demonstration projects," *IEEE Trans. Power Energy*, vol. 5, no. 4, pp. 78–94, Jul./Aug. 2007.

[26] T. L. Saaty and K. P. Kearns, "Chapter 3 the analytic hierarchy process," in *Analytical Planning: The Organization of System*, ser. International series in modern applied mathematics and computer science, 1st ed. New York, USA: Pergamon, 1985.

[27] S. Shao, "An approach to demand response for alleviating power system stress conditions due to electric vehicle penetration," Ph.D. dissertation, Elect. Comput. Eng., Virginia Polyech. Inst. State Univ., Blacksburg, VA, USA, Oct. 2011.

[28] EPA, National Action Plan for Energy Efficiency Sector Collaborative on Energy Efficiency Office Building Energy Use Profile Jul. 2008. [Online]. Available: http://www.epa.gov/cleanenergy/documents/suca/sector_collaborative.pdf

D. Bian (S'11) received the B.S. degree in electrical and computer engineering (ECE) from Tongji University, Shanghai, China, in 2007 and the M.S. degree in electrical and computer engineering from Virginia Polytechnic Institute and State University, Blacksburg, VA, USA, in 2011, where he is currently pursuing the Ph.D. degree in electrical engineering.

His research interests include smart grid, demand response, and communication methods for power systems.

M. Pipattanasomporn (S'01–M'06–SM'11) received the Ph.D. degree in electrical engineering from Virginia Polytechnic Institute and State University, Blacksburg, VA, USA, in 2004.

She joined Virginia Polytechnic Institute and State University's Department of Electrical and Computer Engineering as an Assistant Professor in 2006. She manages multiple research grants from the U.S. National Science Foundation, the U.S. Department of Defense, and the U.S. Department of Energy, on research topics related to smart grid, microgrid, energy efficiency, load control, renewable energy, and electric vehicles. Her research interests include renewable energy systems, energy efficiency, distributed energy resources, and the smart grid.

Saifur Rahman (S'75–M'78–SM'83–F'98) is the Director of the Advanced Research Institute at Virginia Polytechnic Institute and State University, Blacksburg, VA, USA, where he is the Joseph Loring Professor of Electrical and Computer Engineering. He also directs the Center for Energy and the Global Environment at the university

Prof. Rahman served as the Vice President of the IEEE Publications Board, and a member of the IEEE Board of Governors in 2006. He is a distinguished lecturer of the IEEE Power and Energy Society, and has published in the areas of smart grid, conventional and renewable energy systems, load forecasting, uncertainty evaluation, and infrastructure planning. Between 1996 and 1999, he was a Program Director in engineering directorate of the National Science Foundation. From 2009 to 2013, he served as a vice president of the IEEE Power & Energy Society and a member of its Governing Board. He is a member-at-large of the IEEE-USA Energy Policy Committee. He is the Editor-in-Chief of the *IEEE Electrification Magazine*.