An Approach for Demand Response to Alleviate Power System Stress Conditions

Shengnan Shao, *Student Member, IEEE*, Manisa Pipattanasomporn, *Member, IEEE,* and Saifur Rahman, *Fellow, IEEE*

Abstract—**Along with the growth of electricity demand and the penetration of intermittent renewable energy sources, electric power systems face more and more stress conditions especially in distribution networks. To alleviate power system stress conditions, this paper proposes an approach for implementation of demand response to control 240V loads at the distribution level. These loads include HVACs, water heaters, and clothes dryers. A multi-layer demand response model is developed that takes into account both utilities' concern of load reduction and consumers' concerns of convenience and privacy. Analytic hierarchy process (AHP) is adopted to take into consideration opinions from all stakeholders in order to determine the priority and importance of various consumer groups. The proposed demand response strategy also includes the control algorithms at the appliance level, considering their dynamic priorities based on the consumers' real-time needs. Simulation results show that the proposed demand response strategy is capable of managing the distribution circuit loads to alleviate power system stress conditions.**

Index Terms—**Demand Response (DR), Analytic Hierarchy Process (AHP), Home Area Network (HAN), distribution network**

I. Introduction

Over the last several decades electric utilities around the world have deployed various types of demand response (DR) programs to reduce their peak loads during stressed conditions when the available generation reaches its limit. [1] Reference [2] lists power system stress condition modes and possible causes. Mainly, system stress situations arise during special events, for example the lack of available generation, or the severe increase in system peak loads due to weather conditions. Recently, with the introduction of highly fluctuated and intermittent sources of generation like solar and wind, electric power systems can face more serious risks of stress conditions. For a certain demand side management (DSM) programs, the end-use high voltage (240V) load (e.g., air conditioners, electric water heaters, and clothes dryers) can be turned off or cycled during times of generation shortage based on the contracts between the utility and the consumers. [3]-[5] Time-of-use pricing and dynamic pricing programs can also be implemented as a tool to perform peak shaving. However, these one-way demand management strategies bring two major problems: 1) the utility may not be confident about the control results due to the lack of feedback information; 2) the consumers have to sacrifice their convenience since the control is in the hand of utilities.

Recently, with the gradual introduction of the smart grid [6] and its enabling technologies [7], the development of demand response programs can be more creative and flexible with many more possible options. [8]-[11] Authors in [12] provide an overview of DR strategies in commercial buildings, while authors in [13] provide a scoping study that summarizes and evaluates the existing methods for residential demand response. While demand response applications in industrial and commercial sectors have been well studied [11], [14]-[16], there is a lack of studies which address the issue of demand response strategies that can provide both load reshape assurance for utilities and demand control choices for consumers.

This paper proposes a multi-layer demand response strategy in which a utility can announce a demand limit and allocate the demand reduction to each consumer and the consumers will have the freedom to choose what kind of loads to be controlled. From the utility side, the demand limit assignment to each consumer is a type of resource allocation problems, which can be determined by analytic hierarchy process (AHP). [17] From the consumer side, the demand response is an energy management tool within the home/building area network (HAN/BAN) to meet the demand limit based on consumers' preferences. This proposed approach can be customized to perform demand response in various segments and sizes of the network, for example, at the feeder level, at the distribution circuit level, and at the substation level. In the context of smart grid, a substation can dynamically compute the load reduction necessary when the system is under stress. The amount of load reduction necessary can be a function of cost of generation, adverse environmental impact (e.g., carbon footprint, ground level ozone concentration), or just simply not enough generation being available to meet the load.

The paper is organized as follows. Section II presents the design of the multi-layer demand response. Section III describes the demand limit allocation methodology using AHP. Section IV describes the demand response strategy in HAN/BAN level. Section V describes the case study and shows the simulation results for both circuit level and household example. Research findings and key highlights are summarized in Section VI.

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S. Shao is with Virginia Tech – Advanced Research Institute, Arlington, VA 22203 USA (e-mail: sshao@vt.edu).

M. Pipattanasomporn is with Virginia Tech – Advanced Research Institute, Arlington, VA 22203 USA (e-mail: mpipatta@vt.edu).

S. Rahman is professor and director of Virginia Tech – Advanced Research Institute, Arlington, VA 22203 USA (e-mail: srahman@vt.edu).

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II. Design of Multi-layer Demand Response

The design of the proposed multi-layer demand response (DR) is shown in Fig. 1 with the following four layers and notations:

- Layer 1: Wide area network (Utility level)
- Layer 2: Field area network (Transmission level)
- Layer 3: Neighborhood area network (Distribution Feeder level)
- Layer 4: Home/Building area network (HAN/BAN) and smart appliances (Consumer and appliance level)

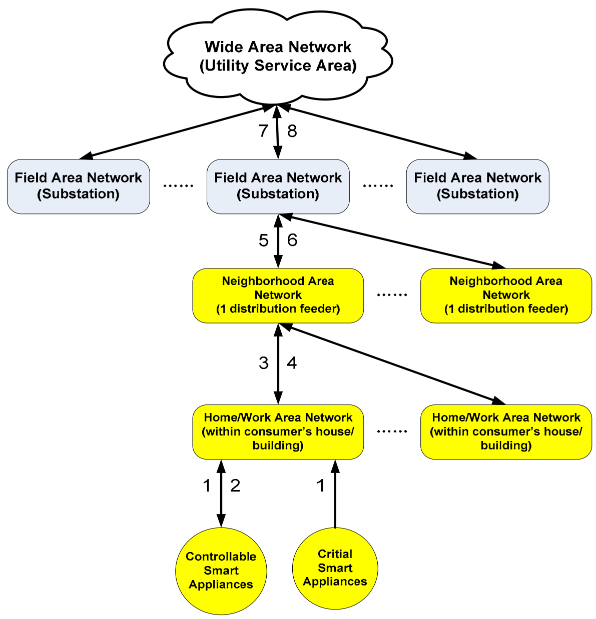


Fig.1. The proposed multi-layer demand response structure.

The numbers represent interactions between layers, and are described below.

1. Report to the home/work area control center the proposed demand in the next time interval.
2. Approve or deny the proposed demand in the next time interval.
3. Report to the neighborhood area network (NAN) control center the aggregation of the home/building demand in the next time interval.
4. Assign the demand limit for each building in the area in the next time interval.
5. Report to the field area network (FAN) control center the aggregation of the demand in NAN level in the next time interval.
6. Announce the demand limit for the next time interval.
7. Report to the wide area network (WAN) center the aggregation of the demand in FAN level in the next time interval.
8. Announce the demand limit for the next time interval.

The focus of this paper is on Layer 3 – the distribution feeder and Layer 4 – the home/building area network and the smart appliances.

A. Layer 1: Wide Area Network (WAN)

When there is a supply limit, which can cause by generation/transmission outages, or solar/wind power fluctuation, the utility will declare a demand limit event. According to the reported demand from each substation and the load priority of each substation (e.g. substation serving hospitals, commercial buildings, residential customers), the utility will decide how much load to shed for each substation. This can be determined based on load priorities and optimal power flow (OPF) calculations, which takes into consideration capacity limit, economic dispatch and so on.

B. Layer 2: Field Area Network (FAN)

According to the demand limit given by a utility to the substation and demand reported from each feeder, the demand limit is further distributed to each neighborhood area network (i.e. distribution feeder) based on their capacities and importance.

C. Layer 3: Neighborhood Area Network (NAN)

When the utility issues a demand limit event, the task for this layer is to determine how much demand needs to be shed from each residential house or commercial building. This process is divided into two steps: a) demand limit allocation to each consumer group (e.g. residential and commercial); and b) demand allocation to each end-use unit (e.g. homes and buildings). Note that the demand limit event can be initiated based on the capacity contract with the utility.

D. Layer 4: Home/Building Area Network (HAN/BAN)

Inside each residential house, there will be a home area network (HAN) control center to manage the total household demand by controlling the controllable smart appliances. Similarly, a building area network (BAN) is the management network in a commercial building. Each smart appliance will have an interface to receive the control signal from the HAN/BAN center and to report its own status. Right now, many communication standards are applied to HAN/BAN, such as Zigbee, 802.11, Bluetooth and others. The most common HAN/BAN network is based on wireless communications that are fast enough to transmit data and control signals, and more importantly secure. Commercial products are available in the market today for in-home electricity monitoring, such as The Energy Detective Devices (TED), Google Power Meters, and Microsoft Holms. [18]-[19]

III. Demand Limit Allocation in NAN

In the Neighborhood Area Network (NAN), the demand limit is assigned to each consumer group using AHP and ultimately allocated to each end-use unit with consideration of fairness.

A. Demand Limit Allocation with AHP

In this paper, AHP is adopted to determine the demand reduction allocation to different consumer groups when there is a supply limit event. This paper considers five consumer groups, which are residential homes, office buildings, schools, public assemblies and fast food service units. Since the demand side management here can be considered as a kind of resource allocation problem, the Analytic Hierarchy Process (AHP) with the Expected Priority (EP) method described in [20] is proposed to address the problem.

To model the demand limitation allocation using AHP, the goal, the criteria, and possible alternatives must be defined. The goal is the demand limit amount to be assigned. The criteria are opinions from customers, experts and the utility. The alternatives are the consumer groups according to the principle building activities, described in [21]. Fig. 2 shows the AHP structure for the demand limit allocation.

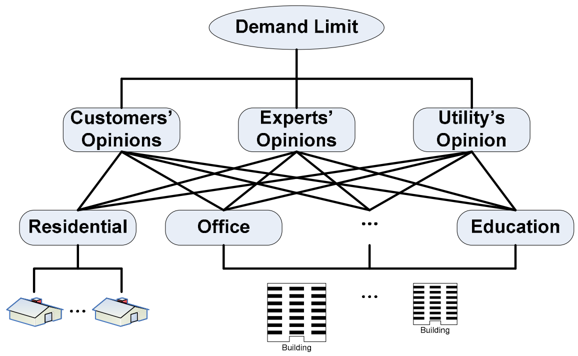


Fig. 2. AHP structure for the demand limit allocation.

1) Step 1: Survey customers, experts and the utility

With AHP, opinions from regular customers, experts and the utility are all taken into consideration. A survey is conducted to determine how customers, experts and the utility perceive the importance of each consumer group differently during various time periods (e.g. day and night). The weight of customers' opinions, experts' and utility's are derived according to Saaty's levels:

- 1, as equal;
- 3, as a little more important;
- 5, as more important;
- 7, as much more important; and
- 9, as extremely more important.
- 2,4,6,8 are intermediate values.

Using the Eigen value method, the weight for each criteria group's opinion are given by w_c, w_e, w_u, in which: w_c is the weight of the opinions from the regular customer group, w_e is the weight of the opinions from the expert group and w_u is the weight of the opinion from the utility. $w_c+w_e+w_u=1$.

2) Step 2: Create pair-wise comparisons

Table I shows an example of a pair-wise comparison result during the daytime from one expert. As shown, during the daytime, the expert perceives that office buildings are more important than residential buildings, and fast food service is a little more important than residential buildings while office buildings are a little more important than fast food service.

TABLE I. A PAIR-WISE COMPARISON DURING THE DAY TIME

	Residential	Office	Public Assembly	School	Fast food
Residential	1	1/5	1/2	1/6	1/3
Office	5	1	4	1/2	2
Public Assembly	2	1/4	1	1/5	1/3
School	6	2	5	1	2
Fast Food	3	1/2	3	1/2	1

The corresponding judgment matrix (J) can be derived from Table I as:

$$J=\begin{bmatrix} 1 & 1/5 & 1/2 & 1/6 & 1/3 \\ 5 & 1 & 4 & 1/2 & 2 \\ 2 & 1/4 & 1 & 1/5 & 1/3 \\ 6 & 2 & 5 & 1 & 2 \\ 3 & 1/2 & 3 & 1/2 & 1 \end{bmatrix}$$

The judgment matrix can change according to the opinions from different customers, experts and the utility, as well as the number of customers/experts/utilities surveyed.

3) Step 3: Define the load categories

According to reference [22], in a residential house, 240V loads, including HVACs, water heaters and clothes dryers, are considered as controllable loads. All other loads, such as refrigerators, TVs, computers and other 110V plug loads, are considered critical or the loads should not be controlled. This is to minimize consumers' inconvenience.

For commercial buildings, the only controllable load is HVAC while all other loads are critical loads.

4) Step 4: Calculate the demand limit allocation for each customer group

The Eigen vector w, which makes $Jw=\lambda_{max}w$, represents the final priorities of the five consumer groups (residential, offices, schools, public assemblies and fast food) from one person's opinion. Here λ_{max} is the maximum Eigen value.

Assume that the survey has been conducted for n regular customers, m experts and 1 utility to decide the priorities for each consumer group. Therefore, for n regular customers, there will be n vectors, and the final priority decision vector is:

$$V_c=\frac{w_c}{n}\sum_{k=1}^{n}\overline{w}_k \quad (1)$$

Where:

- V_c is the priority decision vector of the regular customer group;
- $\overline{w}_k$ is the kth customer's opinion vector.

Similarly, the final priority decision of the expert group is:

$$V_e=\frac{w_e}{m}\sum_{j=1}^{m}\overline{w}_j \quad (2)$$

Where:

- V_e is the priority decision vector of the expert group;
- $\overline{w}_j$ is the jth expert's opinion vector.

The final priority decision of the utility is:

$$V_u=w_u\overline{w} \quad (3)$$

Where:

- V_u is the priority decision vector of the utility;
- $\overline{w}$ is the utility's opinion vector.

By combining the final decision vectors of the regular customer group, the expert group and the utility, the final decision for the demand limit allocation in each time slot i is:

$$\max \sum_{l=1}^{N} (V_c + V_e + V_u) \times \hat{x}_l^i \quad (4)$$

Subject to:

$$\sum_{l=1}^{N} \hat{x}_l^i \le D_l^i$$

$$\forall \hat{x}_l^i, l \in \{1, \cdots, N\}, \hat{x}_l^i \le x_l^i$$

Where:

- N is the number of consumer groups that are compared with pair-wise method. For this case study, N=5;
- D_l^i is the total demand limit for all controllable loads;
- $\hat{x}_l^i$ is the demand limit for controllable loads assigned to the lth consumer group in time slot i;
- x_l^i is the original total controllable demand for the lth consumer group without limitation in time slot i.

B. Demand Limit Allocation for Each Building

After the demand limit for each consumer group has been decided, the demand limit has to be assigned to each residential house and commercial building.

1) Residential customers:

For residential houses, the demand limit is determined by demand deduction from the sorted consumption queue. Fig. 3 shows the methodology to determine the demand limit amount allocated to each end-use unit. This methodology can be explained as follows: Firstly, the NAN control center sorts all reported demand (kW). Then, the demand limit for each house (red line) is set at the point that the total household demand to be served (shadow area) is less than or equal to the residential allocation of the supply limit.

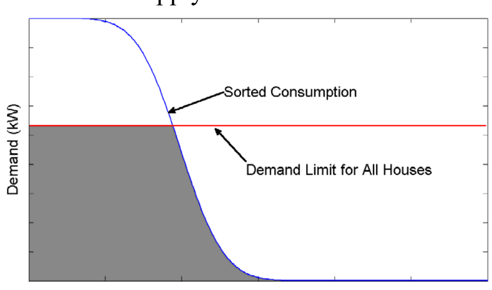


Fig. 3. Sketch of sorted consumption queue and demand limit for each house.

2) Commercial customers:

For commercial buildings, the controllable demand limit allocation will be determined proportional to the building size.

IV. Demand Response in HAN/BAN

The household load is divided into two categories according to Section III: critical and controllable. The critical loads will only report their status while controllable loads can be controlled by the HAN/BAN control center according to the assigned demand limit. The DR strategy for a residential house is that when there is a demand limit, the control center will check if the household demand in the next time interval will be over the assigned limit. If yes, the control center will deny demand requests from some non-critical smart appliances according to customer pre-set preferences.

If the HAN control center sees the total household demand exceeds the demand limit, demand response actions will take place. The demand response in the HAN/BAN is performed as follows:

Step 1. Set the load priority. e.g. water heater is of the highest priority, HVAC is the second and clothes dryer is of the lowest priority.

Step 2. Set the preference. e.g. clothes drying must be finished by midnight. Room temperature should not be higher than 81°F.

Step 3. Perform demand response based on the pre-set load priority and preferences. When the HAN/BAN control center sees the preferences are being violated, the corresponding loads' priorities will be temporarily raised to the highest.

- For HVACs, the DR strategy is:
  - Turn the AC unit OFF once the demand limit signal is received and the AC is not of high priority.
  - Force the unit ON when the room temperature exceeds the pre-set comfort range.
- For water heaters, the DR strategy is:
  - Turn the water heater OFF once the demand limit signal is received and the water heater load is not of high priority.
  - Force the unit ON when the hot water temperature falls below the pre-set comfort range.
- For clothes dryers
  - Turn OFF the heating coils in the clothes dryer once the demand limit signal is received and the clothes drying load is not of high priority.
  - Force the unit ON when the HAN control center foresees that (a) the clothes drying job will not finish within the pre-set duration; (b) the heating coils' off time reaches the maximum limit.

For commercial buildings, the only non-critical load is the space heating in winter and space cooling in summer. Therefore the control strategy is to shut down the HVAC if the room temperature is within the pre-set comfort range. If the room temperature is going out of the comfort range, the control of the specific commercial building will be denied. In that case, other commercial buildings may have to assume more demand reduction.

The smart appliances will have two-way communication with the HAN/BAN control center. Each smart appliance has an IC built in to report the status and to receive the control signal. Recently, some home electronic companies such as General Electric have already started to produce smart appliances with IP based remote control signal receiver. [23]

V. Case Study

To study the impact of the multi-layer demand response strategy on load shape and load factor, a distribution network in the Virginia Tech Electric Service (VTES) area in Blacksburg, VA is taken as a case study.

A. Cast Study Description

The case studies target on a distribution circuit noted as Circuit 9 in the VTES service area. There are 34 laterals with 117 transformers serving 761 residential customers and 9 commercial customers including 2 schools, 1 office building, 5 public assemblies (2 churches, 2 parks and the aquatic center), and 1 seven-eleven, counted as 1 food service. As far as the contract from the local utility is concerned, VTES purchases electricity at 69kV from American Electric Power (AEP). Fig. 4 shows the map of the area for case studies.

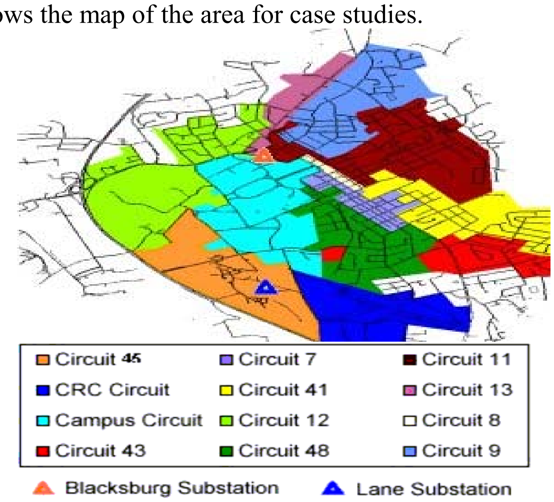


Fig. 4. Virginia Tech Electric Service (VTES) for Case Study [24].

The customers served in the area can be categorized into five consumer groups: residential, office, public assembly, school and food service. The case studies in this paper focus on demonstrating demand response strategies in Layer 3 and 4 described in Section II.

In Layer 1 and Layer 2, the demand limit is set based on the agreement between VTES and AEP. To avoid high demand charge, the local generation is used to cover partial loads. When there is a high peak demand, VTES will issue the supply limit based on their contract capacity with AEP and local generation capacity for each feeder in the whole service area. In Layer 3, AHP will be conducted to allocate the limit to each consumer group and in Layer 4 demand response within the HAN/BAN will be performed to meet the given limit.

Fig. 5 shows the total feeder demand without any demand response in both summer and winter for a 24-hour period.

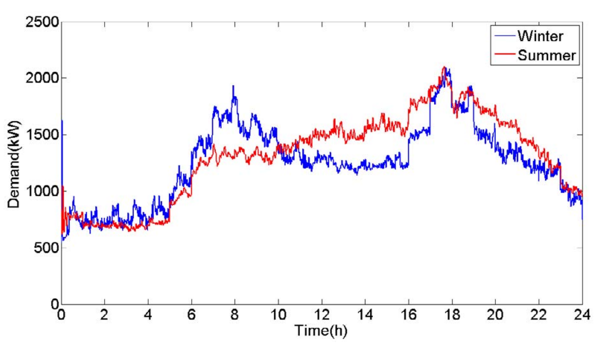


Fig. 5. Load profile of a distribution circuit in summer and winter for a 24-hour period.

B. Demand Response Results

1) AHP Results

Once the circuit of interest receives the supply limit from the substations, AHP will be used to decide the allocation for each customer group. The multi-layer DR system structure for the test cases is shown in Fig. 6.

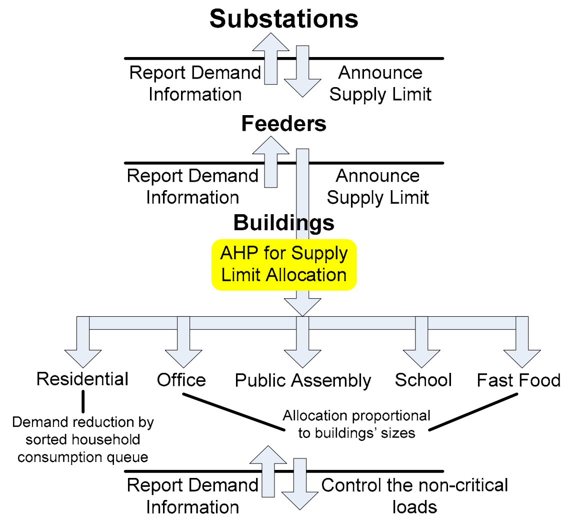


Fig. 6. Multi-layer DR structure.

Practically, an extensive survey is needed for the AHP opinion input. The whole day is divided into two judgment categories: daytime and night-time. The pair-wise opinions are generated for consumers, experts and the utility serving the area. Consistency ratios (CR) are checked for each group of opinions to remove the opinions that are not consistent. The final AHP results are shown in Table II.

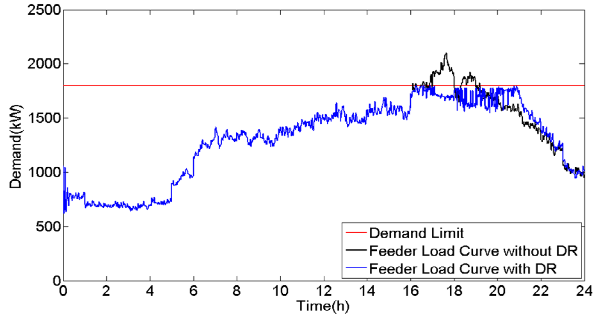
TABLE II. AHP JUDGMENT RESULTS

	Residential	Office	Public Assembly	School	Fast Food
Daytime	0.0737	0.4249	0.0408	0.3052	0.1554
Nighttime	0.3920	0.1032	0.0827	0.1001	0.3220

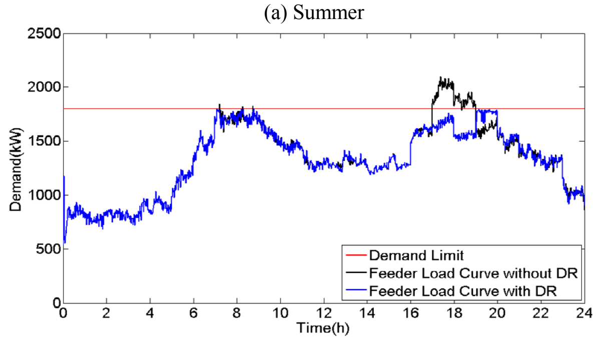
The AHP judgment results show that office and school buildings are more important during the daytime, while residential and fast food service are more important during the nighttime. This result is intuitive.

2) Circuit Load Curves w/ and w/o Demand Response

This section presents the demand response simulation results for the distribution circuit in summer and winter under different supply limits. Fig. 7 as described below shows the results of demand reduction and load shifting for both residential and commercial buildings when the demand limit is 1800 kW.



(a) Summer



(b) Winter

Fig. 7. Load profiles of a distribution circuit w/ and w/o DR when the demand limit is 1800kW.

3) Demand Response Details in a Home Area Network

Based on the proposed DR strategy, consumers must set their load priority and preference beforehand to decide the load control sequence during the demand limit event. For the target home, it is assumed that the load priority and preference are selected as shown in Table III.

TABLE III. PRE-SET LOAD PRIORITY AND PREFERENCE

Load Type	Load Priority	Preference
Water Heater	1	Water temp >= 100°F
HVAC	2	Room temp < 80°F
Clothes Dryer	3	Complete in 3 hours OFF time limit: 30 min.

This setting implies that the clothes drying load is the first to be shed during a demand limit event. This is followed by HVAC and finally water heater. The preference is also set, as shown. This will change the pre-set load priority dynamically once the HAN control center perceives that the preference setting is violated.

Assuming the demand limit assigned to a residential house during 15:00-18:30 is 8kW. Therefore the HAN control center needs to manage the total demand below this demand limit.

Between 15:00 and 17:05, the total household load does not exceed the 8kW limit, therefore no DR is performed.

Between 17:05 to 17:17, the water heater starts to keep the hot water temperature within the comfort range. At the same time, the clothes dryer is ON, the total demand now exceeds the 8kW limit. As the clothes dryer is of lower priority, the heating coil is turned off to meet the household assigned demand limit.

Between 17:17 and 17:30, as the water heater keeps running and as long as the clothes dryer heating coil is turned ON, the total demand will exceed the demand limit. Therefore the clothes dryer heating coil is kept OFF for the whole 25 minutes starting from *17:05*.

Between 17:30 and 17:42, as the water heater stops running due to the hot water temperature reaching the upper bound of the setting range, the total household demand will not exceed the demand limit even with the clothes dryer heating coil ON. Therefore the clothes dryer demand resumed to finish the heating job. Note that in the previous control period, the clothes dryer's heating coil OFF time did not exceed the heat loss limits. The heating coil resume time will be equal to the shut down time for compensation.

Between 17:42 and 18:30, the total household demand is not exceeding the demand limit. Therefore, no DR is performed.

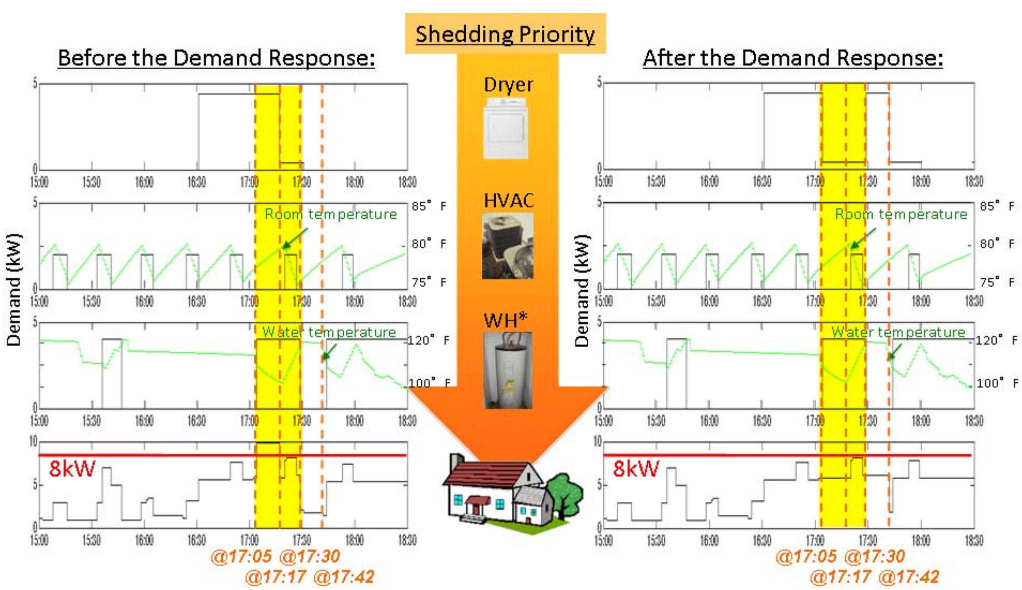


Fig. 8. Household load profile during 17:00 - 20:30 showing load control events before (left) and after (right) the demand response (WH* = water heater).

VI. Conclusions

Various demand response programs have long been implemented to deal with power system stress conditions. However, traditional demand side management strategies cannot provide utilities with the assurance of load curve reshape. Moreover, it deprives consumers' convenience and comfort because the consumers do not have control over the use of their own loads.

This paper proposes a multi-layer demand response strategy to address the problem of system stress conditions at the distribution network level. The proposed methodology is designed to guarantee the demand reduction to meet the demand limit when there is a supply shortage. It provides consumers with full control of their own loads with pre-set load preferences. AHP is adopted to perform the demand limit allocation to different consumer groups.

Simulation results show that the proposed multi-layer demand response can fulfill the task of demand reduction during a system stress event; and the load control details show that the proposed DR strategy will not violate the consumers' convenience and preferences.

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VIII. Biographies

Shengnan Shao (S'08 - IEEE) is pursuing her Ph.D. degree in the Department of Electrical and Computer Engineering at Virginia Polytechnic Institute and State University, VA, USA. She received her M.S. degree in 2007 and B.S. degree in 2005 in Electrical Engineering from Tsinghua University (THU), Beijing, China. She is now a research assistant at the Advanced Research Institute of Virginia Tech. She is a member of the team working on Intelligent Distributed Autonomous Power Systems (IDAPS) project at the Virginia Tech – Advanced Research Institute. Her fields of interest include power distribution, smart grid and renewable energy systems.

Manisa Pipattanasomporn (S'01, M'06 - IEEE) joined Virginia Tech's Department of Electrical and Computer Engineering as an assistant professor in 2006. She received her Ph.D. in electrical engineering from Virginia Tech in 2004. She received the M.S. degree in Energy Economics and Planning from Asian Institute of Technology (AIT), Thailand in 2001 and a B.S. degree from the Electrical Engineering Department, Faculty of Engineering, Chulalongkorn University, Thailand in 1999. She is currently researching the application of a specialized microgrid called the Intelligent Distributed Autonomous Power Systems (IDAPS) to improve the resiliency of electrical energy infrastructures. Her fields of interest are renewable energy systems, distributed energy resources and critical infrastructures.

Saifur Rahman (S'75, M'78, SM'83, F'98 - IEEE) is the director of the Advanced Research Institute at Virginia Tech 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. Professor Rahman has served as a program director in engineering at the US National Science Foundation between 1996 and 1999. He has served on the IEEE PES Governing Board as VP of industry relations, and VP of publications between 1999and 2003. In 2006 he served as the vice president of the IEEE Publications Board, and a member of the IEEE Board of Governors. In 2008 he is serving as the vice president for New Initiatives and Outreach for the IEEE Power & Energy Society and a member of its Board. He is a member-at-large of the IEEE-USA Energy Policy Committee. He is a distinguished lecturer of IEEE PES, and has published over 300 papers on conventional and renewable energy systems, load forecasting, uncertainty aluation and infrastructure planning.