# Demand Response as a Load Shaping Tool in an Intelligent Grid With Electric Vehicles

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***Abstract*—As electric vehicles (EVs) take a greater share in the personal automobile market, their penetration will cause overload conditions at the distribution transformer. This paper focuses on the impacts of charging EVs on residential distribution networks including the transformer. The cost to accommodate a large-scale EV penetration by upgrading distribution transformers can be prohibitive. To alleviate the potential new load peaks with minimal infrastructure investments, a demand response strategy is proposed as a load shaping tool that allows improvement in distribution transformer usage. With the proposed strategy, consumers' preferences, load priorities, and privacy can be taken into account.**

***Index Terms*—Demand response (DR), electric vehicle (EV), home area network (HAN), load shaping.**

## I. Introduction

DUE TO GROWING concerns on energy conservation and the environment, as well as foreign oil dependency in the United States [1], [2], electric vehicles (EVs) have emerged as a promising alternative in recent years that use electricity to displace a significant fraction of fleet petroleum consumption [3]–[5]. The overall fuel conversion efficiency of EVs is approximately at 22.5%–45% [6]–[8], while that of conventional vehicles is estimated at only about 20%. As EVs move toward commercialization, it is expected to gain high market share in the next few years [9], [10].

Majority of previous work related to EVs focuses on the impact of charging EV fleets on large-scale electric power systems. For example, the authors of [1], [3], [11]–[13] studied the EV penetration and optimistically concluded that EVs would only slightly increase the national system load peak. Oak Ridge National Laboratory (ORNL) [9] performed a thorough analysis of EV penetration into the regional power grid, and reported that quick charging EVs during evening hours could create much higher new peaks by 2030. Hence, integrating EV fleets into nationwide electric power networks will result in new challenges that involve investments in generation, transmission, and distribution infrastructures.

That being said, since the EVs are in fact integrated into the electric power systems by plugging them at consumer premises, under the right conditions, there may be significant overload conditions for the distribution transformer. However, very limited number of papers discussed the impact of EV penetration at the distribution level [14], [15]. As the population density is much higher in metropolitan areas, the EV adoption may also show a cluster effect [16]. On the other hand, in a larger system where an EV fleet is present, the problem may not be significant, because where and when the EVs are connected are diversified.

This paper focuses at the distribution transformer level. Then, a consumer-centric demand response (DR) strategy assisted by a home area network (HAN) is proposed to perform load shaping and thus avoiding the transformer overload problem. In other words, to accommodate the additional EV load, we are in need of a proper load shaping tool that will delay or avoid the distribution transformer upgrade and offer more optimum utilization of this asset.

According to the Federal Energy Regulation Commission, demand response (DR) is defined as "changes in electric usage by demand-side resources 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" [17]. Recently, many demand response strategies have been introduced to solve peak load shedding and shifting problems [18]–[21]. The authors of [22] provided an overview of DR strategies in commercial buildings, while the authors of [23] summarized and evaluated the existing methods for residential demand response. While demand response applications in industrial and commercial sectors have been well studied [21], [24]–[26], there is a lack of studies which address the issue of consumers managing their household loads without sacrificing their comfort level or privacy.

This paper proposes a demand response strategy as a load shaping tool in the intelligent grid to tackle the problem of distribution transformer overloading. The proposed methodology is helpful to analyze and mitigate the impact of EVs on different transformers of various sizes and types in a larger system. The FERC staff report [17] pointed out that currently available DR programs are categorized into either incentive-based or time-based (TOU, dynamic pricing, critical peak pricing, peak-time rebate, etc.) programs. Since, according to this report, the incentive-based DR programs are responsible for more than 80% of peak demand reduction potential in the United States, this paper focuses on the DR strategy design. This reflects incentive-based DR programs that involve a utility sending some kind of load control signals to the customer. The paper targets the design of DR strategy at the household level which takes into account customers' preference, comfort level, and load priority. The paper is organized as follows. Section II presents a typical distribution

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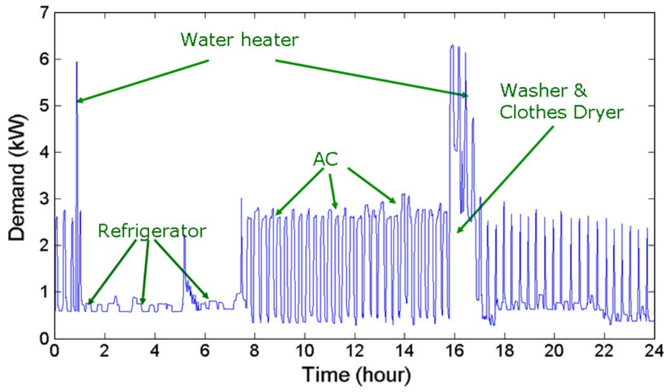


Fig. 1. A 24-h electric power consumption measured from a house in Virginia.

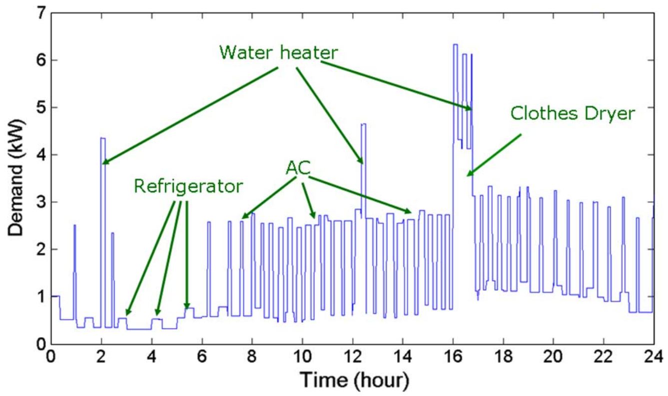


Fig. 2. A 24-h electric power consumption generated from the load model.

transformer load with and without EVs. Section III presents the design of the proposed DR strategy as a load shaping tool. Section IV discusses the implementation of the DR strategy and presents the household and the distribution transformer load profiles after the implementation of DR. Research findings and key highlights are summarized in Section V.

## II. DISTRIBUTION TRANSFORMER LOADING WITH ELECTRIC VEHICLE PENETRATION

In this section, a household load profile and an EV charging profile are presented. A transformer load profile is then generated for a 25 kVA distribution transformer with an assumption that it serves three homes and three EVs. In a metropolitan area, as many as six or seven homes can be connected to a 25 kVA distribution transformer.

### *A. Household Load Profile*

For the purpose of this study, all household loads are classified into two categories: controllable and critical [27]. Controllable loads are defined as loads that can be controlled without noticeable impacts on the consumer's lifestyle. Loads in this category can include space cooling, space heating, water heater, and clothes dryer loads. The other category contains loads that are either very important (critical loads) or loads that cannot be controlled. These include all other loads in a house, such as lighting, refrigeration and other plug loads.

Fig. 1 presents an example of a minute-by-minute residential house load profile for a 24-h period. This reflects the measurement from a house in southern Virginia.

To create household load profiles, controllable load models are developed using a bottom-up approach similar to that presented in [28]. The bottom-up models of all household loads (HVAC, water heater, clothes dryer loads, and the like) are backed up by mathematical formulae [29]–[31]. Load profiles of the critical loads are derived from an industry-accepted load profile database [32]. The description of how the household load models are developed is not the focus of this paper, and is not emphasized here.

Fig. 2 shows the simulation output from the developed load model.

As seen in Figs. 1 and 2, the simulated load model and the measured load data are quite close. The discrepancies come from the fact that the real measured data comes from a specific house, where the modeled house represents a generic construction and usage profile under similar weather conditions.

TABLE I
EVS IN THE U.S. MARKET [34]–[39]

| **Make, Model, Type** | **Battery Size** | **Energy Available** | **All Electric Range** | **Charge Power** |
|---|---|---|---|---|
| GM - Chevy Volt (EV) | 16kWh | 8kWh | 40 mi | 120V 8A<br>120V 12A<br>240V 16A |
| Nissan – LEAF (EV) | 24kWh | 19.2kWh (80%) | 100 mi (US LA4 mode) | 100V 30A |
| Tesla Roadster (EV) | 53kWh | 37.1kWh (5%-75%) | 244 mi (Experiment) | 240V 70A |
| Volvo C30 (HEV) | 24kWh | 22.7kWh | 93 mi (NEDC cycle) | 230V 16A |
| BMW MINI E (EV) | 35kWh | 30kWh | 156 mi (ideal) | 110V 12A<br>240V 48A |

### *B. EV Charging Profile*

Determining EV charge power consumption profiles is a subject of interest in many previous publications. The authors of [33] reviewed several characteristics for evaluation of EV impacts on the grid. Table I shows the key parameters of five major EVs available in the United States [34]–[39]. Each EV has different battery sizes, driving ranges, and charging power.

The detailed case studies in Section IV investigate the impact of charging different types of EVs on the distribution transformer, with various plug-in times and different driving distances. All EV types as shown in Table I are considered. Various plug-in times are considered and are simulated using random functions. Different EV driving distances are simulated using Monte Carlo simulation based on the American daily driving distance distribution [40].

### *C. Distribution Transformer Load Profiles With and Without EVs*

This section illustrates the load profiles of a 25 kVA distribution transformer serving three homes with and without EVs. The EV characteristics used are of Chevy Volt, which has different charging options as shown in Table II.

The simulations below consider two commonly used charging rates: normal and quick charge.

TABLE II
CHEVY VOLT CHARGING OPTION

| Charging Circuit | Charge Power | Charge Duration |
|---|---|---|
| Slow Charge (120V/8A) | 0.96 kW | 8.3 hour |
| Normal Charge (120V/12A) | 1.44 kW | 5.6 hour |
| Quick Charge (240V/16A) | 3.84 kW | 2.1 hour |

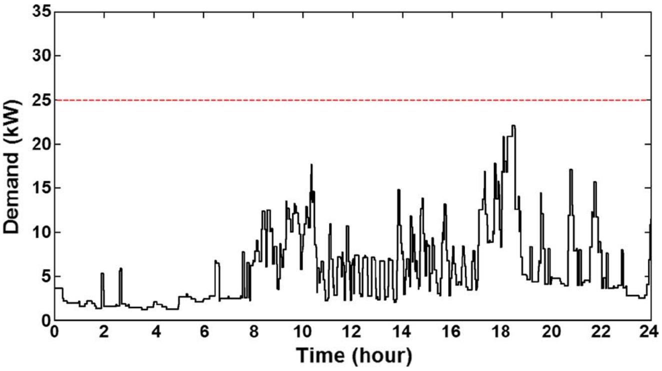


Fig. 3. Load profile of a 25 kVA transformer serving three homes.

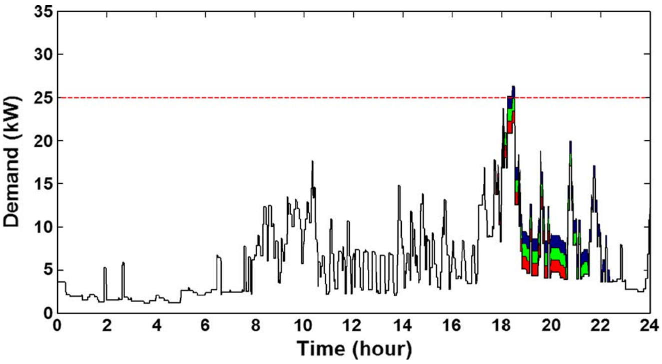


Fig. 4. Load profile of a 25 kVA distribution transformer serving 3 homes and 3 EVs charging at 1.44 kW (normal charge) in the peak evening hours.

*1) Distribution Transformer Load Profile Without EVs:* To study impacts of EV penetration on the distribution transformer, a three-home load profile is generated by using diversified home electricity consumption models (variations of what is shown in Fig. 1). This is shown in Fig. 3.

The simulation result is in line with the fact that, on average, the transformer loading level is about 35% of its rating. This implies that, most of the time, the transformer loading level is less than 8 kW for a 25 kVA transformer. The peak load of this system is about 22 kW, which is well below the transformer rating.

*2) Distribution Transformer Load Profile With EVs—Normal Charge:* With EV penetration, the distribution transformer may be overloaded especially when there are more than one EVs connected to a transformer at the same time. Fig. 4 shows the load profile of a 25 kVA distribution transformer serving three houses and three EVs with normal charge (120 V/1 2 A) profile. The EV plug-in times are determined by a normal distribution function with the mean at 6 P.M. and 1-h variance. It is to be noted that for the normal charge operation, it takes approximately 6 h to complete. The red, green and blue segments in these plots represent the car charging electrical demands.

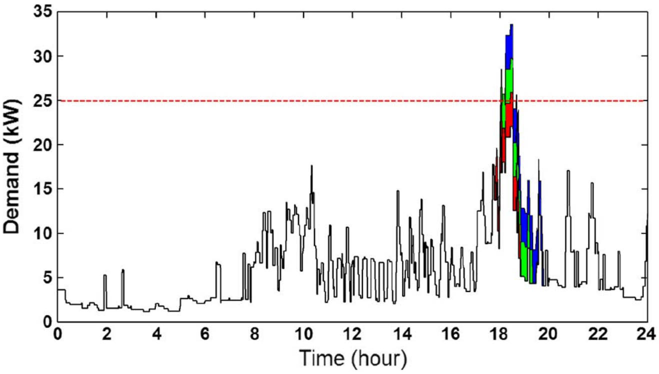


Fig. 5. Load profile of a 25 kVA distribution transformer serving three homes and 3 EVs charging at 3.84 kW (quick charge) in the peak evening hour.

It can be seen that with three EVs charging at about the same time in the evening, the transformer is overloaded for a short period of time. In reality, this short-term transformer overloading is acceptable.

*3) Distribution Transformer Load Profile With EVs—Quick Charge:* Fig. 5 shows the load profile of a 25 kVA distribution transformer serving three homes and three EVs with quick charge (240 V/16 A). The EV plug-in times are determined by a normal distribution function with the mean at 6 P.M. and 1-h variance. For the quick charge, it takes approximately 2 h to complete.

It can be seen that with EV charging during the evening peak time, the 25 kVA distribution transformer gets over loaded more than 130% for about one hour. This may be harmful to the transformer and its service life. Without a proper load shaping tool, the transformer will need to be upgraded.

## III. DESIGN OF A LOAD SHAPING TOOL

To avoid overloading a distribution transformer with high EV penetration, a demand response strategy is proposed as a load shaping tool to ensure safe operation of a distribution transformer. This paper proposes a demand response (DR) strategy to keep the transformer from being overloaded and improve the distribution transformer usage. This strategy also provides consumers freedom to set the load priorities and preferences for individual house load control.

### A. *Infrastructure Requirement*

The implementation of the proposed DR strategy requires a modest infrastructure upgrade at both the distribution level and the house/appliance level.

At the distribution level, a sensor is required at a distribution transformer for load monitoring; and two-way communication is needed between the distribution transformer and the homes it serves. With the load-monitoring device, the distribution transformer can sense its loading level. A demand limit signal is sent to each home through two-way communications when the transformer loading level exceeds its rated capacity. This two-way communication infrastructure can be piggybacked on the existing advanced metering infrastructure (AMI). Fig. 6 depicts the infrastructure required to implement DR at a distribution transformer serving a group of homes.

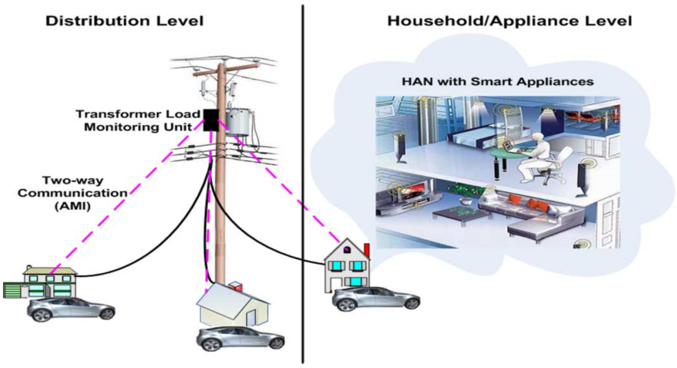


Fig. 6. Infrastructures required to implement DR at a distribution transformer.

To allow in-home load management, real-time electrical energy consumptions of all household loads must be monitored at the household/appliance level. This task can be accomplished by a home area network (HAN) control center, together with smart appliances. The HAN control center embeds with the proposed DR strategy, while the smart appliances are IP-addressable, controllable, and are capable of communicating with the HAN control center. Each smart appliance has an IC built in so that it can report its status and receive the control signal from the HAN control center. Recently, General Electric has introduced smart appliances with an IP-based remote control signal receiver, and an in-home control unit [41].

### B. Description of the Proposed Demand Response Strategy

The proposed demand response (DR) strategy is initiated once the target distribution transformer loading level exceeds its rated capacity. When there is a transformer overloading event, a demand limit is issued to each home connected to that transformer to keep their electricity demand below a certain level. There are many ways to determine the demand limit levels assigned to different homes. The demand limit levels can be flexible and can change in real time depending upon time-varying electricity price signals, real-time electricity usage or other utility-defined factors. In the example presented in the paper the time varying price signals were not considered because first, in most utilities these time varying rates are not in effect, and second, in cases where such rates exist, the differentiation is small enough not to significantly impact our results. Detailed of this analysis can be found in our earlier paper [27]. For the purpose of this study, and to provide a simple demonstration, it is assumed that the demand limit for each home is fixed at a certain value.

Once the HAN control center receives this demand limit signal, demand response (DR) is then performed in real time at the appliance level, given that the load priority and convenience preference are preset as described below.

*1) Load Priority and Preference Setting:* At the household level, before each HAN control center can perform the appliance-level demand response, the homeowner must perform the following steps to let the HAN control center know of their load priority and convenience preference. It is understood that the load priority is customer driven and therefore it will change according to the varying customer preferences.

Step 1) Consumers to set the load priority within a home: In this case, consumers must set and rank (R) the load priority for each controllable load within a home, including HVAC, water heater, clothes dryer, and EV. For example, a consumer may set the EV as the highest priority load in the house; water heater as the second; HVAC as the third; and clothes dryer as the lowest priority.

Step 2) Consumers to set their convenience preference: In this case, consumers must set their convenience preference for each controllable load. This includes: a) the maximum acceptable time to fully charge the EV; b) the maximum acceptable time to finish a clothes drying load; c) the minimum acceptable hot water temperature from the water heater; and d) the maximum acceptable room temperature for the AC load.

*2) Demand Response at the Appliance Level:* Once the demand limit signal is received from the distribution transformer, the HAN control center will compare the total household power consumption $(p_{h,i})$ with the demand limit $(\mathrm{DL}_i)$. As discussed in Section II-A, household loads are classified into controllable and critical loads. In this paper, controllable loads include HVAC, water heating, clothes drying, and EV. The critical load category includes all other loads in a house, such as lighting, refrigeration, and other plug loads. Equation (1) shows the target control function for each house.

$$p_{I,i} + p_{C,i} \leq \mathrm{DL}_i \tag{1}$$

where

$p_{l,i}$ is the power consumption of all controllable loads in time slot $i$, in kW;

$$p_{I,i} = \sum_{j=1}^{N} p_{I_j,i} (I_j = \text{controllable loads}) \tag{2}$$

$p_{l,i}$ is the power consumption of all critical loads in time slot $i$, in kW;

$$p_{C,i} = \sum_{k=1}^{M} p_{C_k,i} (C_k = \text{critical loads}) \tag{3}$$

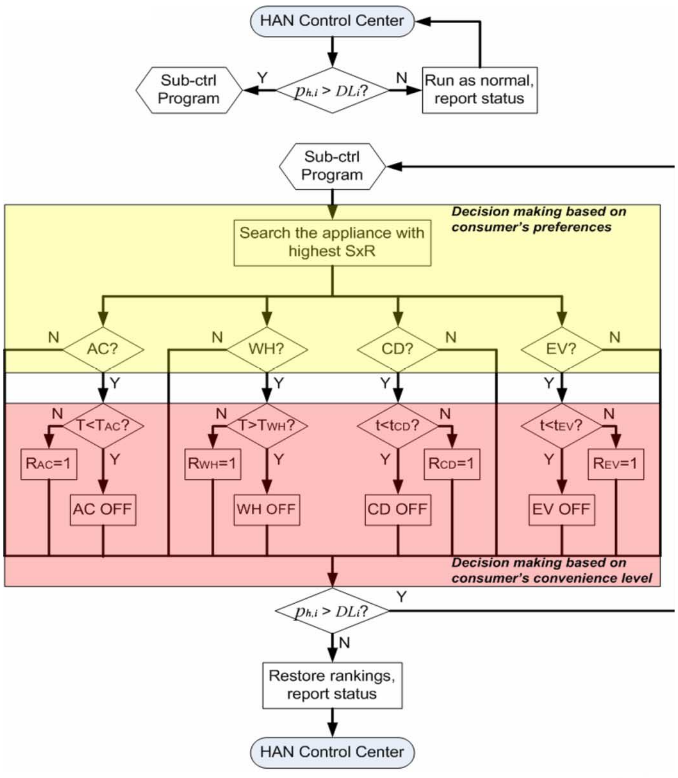
$\mathrm{DL}_i$ is the demand limit assigned for a house in time slot $i$, in kW.

If $p_{h,i}$ is greater than $\mathrm{DL}_i$, demand response will be performed at the appliance level on the controllable loads based on the preset load priority and preference.

Fig. 7 presents the HAN control flow chart that describes the proposed demand response strategy.

The HAN control center will continuously monitor the status of each appliance.

— In a normal situation, the demand limit $(\mathrm{DL}_i)$ for each house is the capacity of the main circuit breaker.



Notes:

*AC = HVAC, WH = water heater, CD = clothes dryer, EV = electric vehicle.

* R is the set of rankings of all the controllable appliances. 1 is the highest. Consumers will pre-select the ranking of each controllable appliance and store them in the HAN control center.

* S is the set of status of all controllable appliances: 1 for ON and 0 for OFF.

* "Run as normal" means no central control, the appliances will run as needed.

Fig. 7. HAN control flowchart.

— Under a stress condition, a demand limit $(\mathrm{DL}_i)$ signal will be issued to each house, according to the transformer capacity and its loading level. When the total household demand $(p_{h,i})$ is lower than $\mathrm{DL}_i$, there will be no central control and the appliances can run as normal. When $p_{h,i}$ is higher than $\mathrm{DL}_i$, there will be the need for central control, which is shown in the flow chart "Sub-ctrl Program."

Firstly, the control center will search for the appliance that are running and with the lowest priority. Then the program will check the related consumer preference. When the HAN control center foresees any violation in consumers' preset convenience preferences, the corresponding load priority will be temporarily raised to the highest $(\mathrm{R} = 1)$. In this case, these loads will not be centrally controlled and run as they are needed.

For example, if the water heater load of one house has the lowest priority and it is controlled to be OFF at that time, once the water temperature falls below the pre-set convenience preference, the priority of the water heater will be changed to the highest. Then, the water heater will be forced ON, and once the hot water temperature is above the preset threshold, the priority of the water heater load will be reset back to its original value.

Once a demand limit event ends, all controllable loads will resume their normal operation. This is what is generally known as load shifting, peak shifting, or demand compensation.

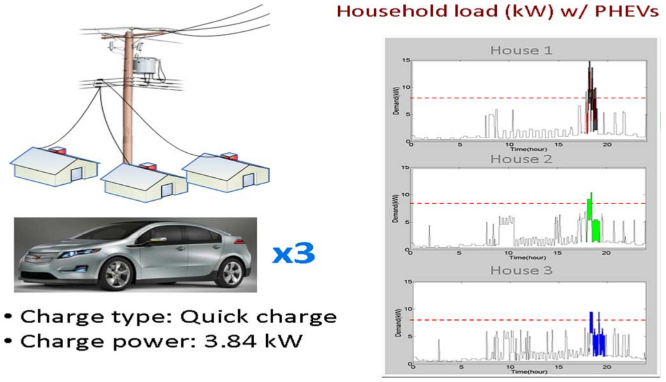


Fig. 8. Scenario for the case study where a 25 kVA distribution transformer serves 3 homes and three EVs. All three EVs are quick charged.

TABLE III
PRESET LOAD PRIORITY AND CONVENIENCE PREFERENCE

| Load Type | Load Priority | Convenience Preference |
|---|---|---|
| EV | 1 | Complete in 2.5 hours |
| Water Heater | 2 | Water temp >= 100°F |
| HVAC | 3 | Room temp < 82°F |
| Clothes Dryer | 4 | Complete in 2.5 hours |

## IV. DEMAND RESPONSE RESULTS

The objective of this section is to demonstrate how the proposed demand response (DR) strategy can be implemented at the household/appliance level to alleviate the overloading condition of a distribution transformer.

### A. Case Study Description

This paper presents the impact of EV penetration and the results of demand response using a case study of a 25 kVA distribution transformer that serves three homes and three Chevy Volts. See Fig. 8. It is assumed that all three Chevy Volts are quick charged during the peak evening hours and as a result, the transformer expects an overloading condition from 17:30 to 20:30. This is the same scenario presented in Section II-C (3).

For the purposes of illustration, it is assumed that the distribution transformer issues a fixed demand limit signal of 8 kW between 17:30 and 20:30 to each home it serves.

### B. Load Priority and Convenience Preference Setting

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

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

### C. DR Results at the House/Appliance Level

Assuming that the target home receives the demand limit of 8 kW between 17:30 and 20:30, Fig. 9 shows the overall result of

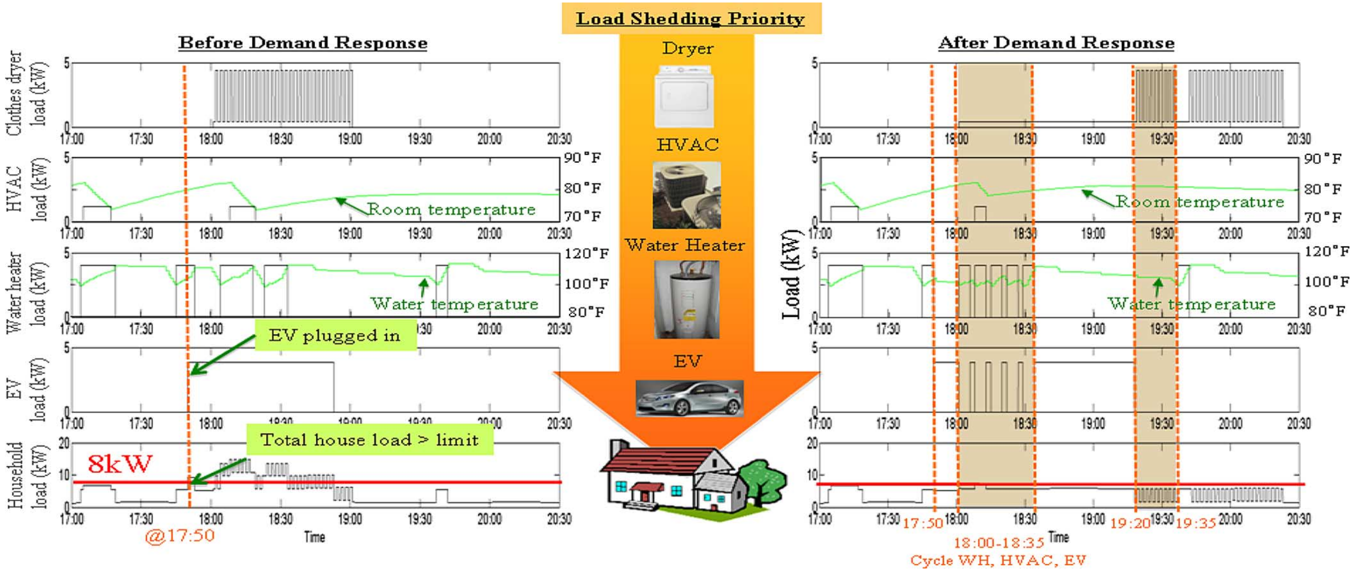


Fig. 9. Household load profile during 17:00–20:30 showing load control events before (left) and after (right) the demand response $(\mathrm{WH}^* = \mathrm{water\ heater})$.

the household load profile from 17:00 to 20:30, 30 min before and after the demand limit event.

*Between 17:00 and 17:50*, the total household load does not exceed the 8 kW limit, therefore no DR is performed.

*At 17:50*, an EV is plugged in. At this time, the water heater is on, and with some critical loads, the total household demand exceeds the supply limit of 8 kW. Since EV is the load with the highest priority, EV will continue charging, while the water heater is turned OFF to save the capacity for charging EV. Between 17:50 and 18:00, the water temperature is always above the 100 °F threshold. Therefore, the load priority remains unchanged.

*At 18:00*, the clothes dryer is turned ON. However, since it has the lowest priority, its heating coil is kept OFF and only the motor part operates to keep the total demand below the 8 kW limit. Between 18:00 and 18:35, the water heater and the HVAC unit have to be ON to keep the temperatures within the required ranges. As a result, the water heater, HVAC, and EV charge have to be cycled. Note that once the water temperature is below 100 °F, the water heater is forced ON; once the room temperature is over 82°F, the HVAC unit is forced ON; and both are turned OFF whenever possible to give priority to EV charging.

*Between 18:35 and 19:20*, clothes dryer heating coil is still kept OFF to allow EV charging and keep the total household load below 8 kW.

*Between 19:20 and 19:35*, the total household load does not exceed the supply limit of 8 kW. No DR is performed. Once the EV is fully charged, the clothes dryer heating coils are allowed to come ON. Room temperature and water temperature are within the preset comfort range, therefore the HVAC and water heater units remain OFF.

*At 19:35*, the hot water temperature falls below the preset comfort range, i.e. 100 °F. Since the water heater has higher priority than a clothes dryer, the water heater is forced ON between 19:35 and 19:40, and clothes dryer heating coils are interrupted momentarily.

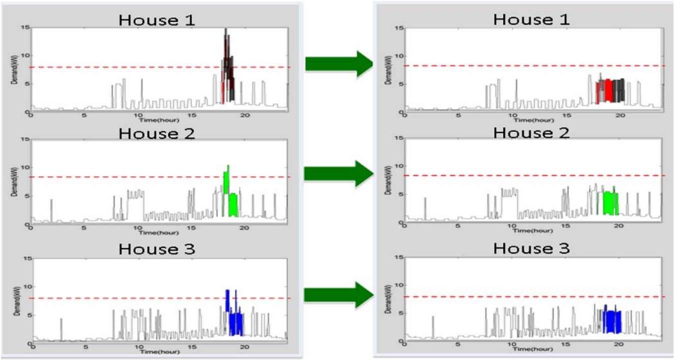


Fig. 10. Load profile for each house before (left) and after (right) the implementation of the proposed demand response strategy.

*Between 19:40 and 20:30*, the total household demand does not exceed the demand limit. Therefore, no DR is performed and the clothes dryer resumes its operation.

Fig. 10 presents the load profiles of the three houses in consideration before and after the implementation of the proposed demand response strategy.

The detailed demand response actions as presented here demonstrate how the proposed DR strategy can be used as a load shaping tool to manage the household load based on the preset load priority and consumers' preference.

### *D. DR Results at the Distribution Transformer Level*

Having seen how the proposed demand response (DR) strategy can be implemented at the household/appliance level, this section presents the aggregated impact of the DR strategy on alleviating the overloading condition of a distribution transformer. While Fig. 6 presents a 25 kVA distribution transformer loading level before the implementation of DR, Fig. 11 illustrates the same after the DR.

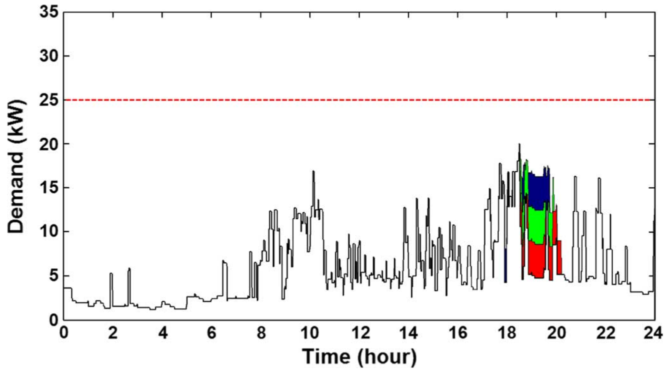


Fig. 11. Distribution transformer loading after DR.

TABLE IV
DISTRIBUTION TRANSFORMER PEAK LOADS WHEN ACCOMMODATING 3 EVS WITH AND WITHOUT DR

| Type of EV | Charge Rate | Peak Load w/o DR (kW) | Peak Load w/ DR (kW) |
|---|---|---|---|
| **Chevy Volt** | 120V/8A | 24.92 | 20.92 |
| | 120V/12A | 26.36 | 21.16 |
| | 120V/16A | 33.56 | 20.04 |
| **Nissan Leaf** | 100V/30A | 31.04 | 20.04 |
| **Tesla Roadster** | 240V/70A | Not Home Charge Option | |
| **Volvo C30** | 230V/16A | 33.08 | 20.04 |
| **BMW MINI E** | 110V/12A | 26.00 | 22.00 |
| | 240V48A | Not Home Charge Option | |

It can be seen that with the implementation of demand response, the transformer overloading problem due to the quick charge of three EVs (Chevy Volt) is solved without adversely impacting the homeowners' convenience and life styles.

### *E. Impact of Different Types of EVs and DR on the Distribution Transformer Loading Level*

The case study shown in the previous section is when three EVs are Chevy Volt with quick charge. Other types of EVs, as shown in Table I (including Nissan Leaf, Tesla Roadster, Volvo C30, and BMW MINI E) are simulated according to the same methodology. To present the worst case scenario, it is considered that the distribution transformer of interest accommodates three houses and three EVs of the same type.

Table IV illustrates the comparison of the peak load increase with EVs, and the peak load reduction with DR. Note again that the original distribution transformer peak load is 22 kW.

It should be noted that when the EV charge rates are lower, the peak loads with DR are higher than the cases with higher EV charge rates. That is because the EVs with lower charging rates can be charged while other household appliances are in operation without violating the household demand limit.

The results indicate that the proposed DR strategy can perform load shaping in a distribution network. The reduction in household electricity consumption will also contribute to alleviating the phase imbalance problem in an area with EV penetration.

## V. CONCLUSIONS

As EVs are taking a greater share in the vehicle market, the impact of EV penetration into the power system has to be carefully examined. Especially in the high population density area, when more and more customers own electric vehicles, high penetration of EVs with uncontrolled quick charge may bring the overloading problem to the distribution transformer. The overloading may shorten the transformer life, and the cost to upgrade a transformer to accommodate EV penetration can be prohibitive.

This paper proposed a demand response strategy as a load shaping tool to improve the distribution transformer utilization, and prevent it from overloading. The application of the proposed DR strategy will help utilities by delaying or avoiding upgrade of the distribution transformers in the areas with high EV penetration. The case study is an example of the methodology for load shaping, which can be expanded to a larger distribution system with different EV charging profiles. By taking into account different customers' preferences and comfort levels, the proposed DR strategy will have minimal impacts on consumers' life styles. In addition, the DR is performed within the home area network to respect the consumers' privacy.

Simulation results show that the proposed load shaping tool can fulfill the task of managing the total demand under the rated power of the distribution transformer. The detailed DR result for a sample home demonstrates how the HAN control center can manage the controllable loads without violating the homeowners' convenience and preset preference.

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