An Approach for Distribution Transformer Management With a Multiagent System

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***Abstract*—The objective of this paper is to propose an approach for smart distribution transformer (TR) management to help implement emergency demand response (DR) at a TR. In this paper, a DR algorithm embedded in a multiagent system is presented. The proposed algorithm ensures that an instantaneous power demand at a TR is kept below a certain demand limit during a DR event while the impacts of demand restrike are minimized. At the same time, homeowners' goals of securing critical loads, mitigating comfort level violation, and minimizing appliance's compensation time during a DR event are taken into account. To validate and evaluate the effectiveness of the proposed DR algorithm, a case study of a TR serving three homes is demonstrated.**

***Index Terms*—Demand response (DR), demand restrike (DRK), multiagent system (MAS), smart distribution transformer management (SDTM).**

NOMENCLATURE

$a_{H,i}, b_{H,i}, c_{H,i}$	Coefficients of quadratic function of $\mathrm{DRKP}_{H,i}(\mathrm{DL}_{H,i})$ of a home $i \in N$ (kW).
$\mathrm{Amp\_Rating}_{H,i}$	Electrical meter service ampere rating of a home $i \in N$ (A).
$[\mathbf{Belief}_{\boldsymbol{H},\boldsymbol{i}}]_{\boldsymbol{M}\mathbf{x1}}$	Belief vector $\mathbb{R}^M$, representing minimum required power demands based on all possible combinations of usage status of power-intensive appliances of a home $i \in N$ (kW).
C	Total number of appliances.
$\mathrm{Cap}_{\mathrm{TR}}$	Distribution transformer (TR) loading capability (kW).
CFP	Call for proposal.
CLV	Comfortable level violation index.
$\mathrm{CLV}_{\mathrm{DRevent}}$	CLV index calculated at the end of a DR event.
$\mathrm{CLV}_{w/o\_\mathrm{DR}}$	CLV index calculated at the same time period where there is no DR event.
$[\mathbf{Comb}]_{\boldsymbol{M}\mathbf{x}\boldsymbol{C}}$	Matrix $\mathbb{R}^{M\times C}$ of combinations of usage status of power-intensive appliances.
$\mathrm{DL}_{\mathrm{AGG}\rightarrow\mathrm{TRA}}$	Demand limit (DL) given to a TRA by a DR AGG (kW).
$\mathbf{DL}_{\boldsymbol{H}}^{*}$	Vector containing optimal DL levels of all homes.
$\mathrm{DL}_{H,i}$	DL level a home $i \in N$ (kW).
$\mathrm{DL}_{H,i}^{*}$	Optimal DL level of a home $i \in N$ (kW).
$\mathbf{DL}_{\boldsymbol{H},\mathbf{fair}}$	Vector containing fair DL levels (kW).
$\mathrm{DL}_{H,\mathrm{fair},i}$	Fair DL level of a home $i \in N$ (kW).
$\mathrm{DL}_{H,\mathrm{req},i}$	DL request to a TRA from a HA $i \in N$ (kW).
$\mathrm{DL}_{H,\mathrm{req,lower},i}$	Lower bound of a DL request of a home $i \in N$ (kW).
$\mathrm{DL}_{H,\mathrm{req,upper},i}$	Upper bound of a DL request of a home $i \in N$ (kW).
$\mathbf{DL}_{\boldsymbol{H},\mathbf{req},\boldsymbol{i}}$	Vector containing DL request of a home $i \in N$ (kW).
$\mathbf{DL}_{\boldsymbol{H},\mathbf{ten}}$	Vector containing tentative DL of all homes (kW).
$\mathrm{DL}_{H,\mathrm{ten},i}$	Tentative DL level of a home $i \in N$ (kW).
DLBCL	DL below critical loads index.
$\mathrm{DRKP}_{H,\mathrm{act},i}$	Actual demand restrike potential at a home level (kWh).
$\mathrm{DRKP}_{H,i}$	Demand restrike potential of a home $i \in N$ (kWh).
$\mathrm{DRKP}_{\mathrm{TR}}$	Demand restrike potential at a TR level (kWh).
$\mathrm{DRKP}_{\mathrm{TR,act}}$	Actual demand restrike potential at a TR level (kWh).
$\mathrm{DRKP}_{\mathrm{TR,exp}}$	Expected demand restrike potential at a TR level (kWh).
M	Number of beliefs in a $\mathbf{Belief}_{\boldsymbol{H}}$ vector.
N	Number of homes served by a TR.
$P_{H,\mathrm{hist},i}(t)$	Similar-day historical power demand of total loads of a home $i \in N$ (kW).
$P_{H,\mathrm{hist,crit,90\%},i}$	Power demand of a home in which an hourly average of critical loads does not exceed 90% of the time $i \in N$ (kW).
$P_{H,\mathrm{hist,crit,max},i}$	Maximum power demand of critical loads of a home $i \in N$ based on similar-day historical data (kW).
$P_{H,\mathrm{hist,max},i}$	Maximum power demand of total loads of a home $i \in N$ based on similar-day historical data (kW).
$P_{H,i}(t)$	Instantaneous power demand of a home $i \in N$ (kW).

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$P_{\mathrm{TR}}(t)$	Total instantaneous power demand at a TR (kW).
$P_{\mathrm{TR,hist}}(t)$	Similar-day historical load profile of a TR during the same period as a DR event (kW).
$P_{\mathrm{TR},w/o\_\mathrm{DR}}(t)$	Actual required power demand of a TR during the same period as a DR (kW).
PEDL	Power exceed DL index.
$\mathbf{PF}_{\boldsymbol{H}}$	Vector containing penalty factors of all homes.
$\mathrm{PF}_{H,i}$	Penalty factor of a home $i \in N$.
$\mathrm{Rated}_{\mathrm{app},k\in P}$	Rated power demand of a power-intensive appliance $k \in P$ (kW).
$\mathbf{[Rated]}_{\boldsymbol{P}\mathbf{x1}}$	Vector $\mathbb{R}^{P}$ containing rated power demand of appliances (kW).
$s_{\mathrm{app},j\in M,k\in P}$	Status of an appliance $k \in C$ of a belief $j \in M$ (0 = off, 1 = on).
t_{eval}	Time that a TRA evaluates $\mathbf{PF}_{\boldsymbol{H}}$.
$t_{\mathrm{DR\_end}}$	End time of a DR event.
$t_{\mathrm{DR\_start}}$	Start time of a DR event.
$\mathrm{temp}_{\mathrm{AC,set}}$	Room temperature set point of an air conditioner (AC) ($F°$).
$\mathrm{temp}_{\mathrm{AC,deadband}}$	AC temperature deadband ($F°$).
$\mathrm{temp}_{\mathrm{room}}(t)$	Room temperature profile during a DR event ($F°$).
$\mathrm{temp}_{\mathrm{water}}(t)$	Hot water temperature profile during a DR event ($F°$).
$\mathrm{temp}_{\mathrm{WH,deadband}}$	Water heater (WH) temperature deadband ($F°$).
$\mathrm{temp}_{\mathrm{WH,set}}$	Hot water temperature set point of a WH ($F°$).

I. INTRODUCTION

NOWADAYS, there is an increasing trend that smart meters, home energy management (HEM) systems, and DR-enabled appliances are becoming more popular [1], [2]. Electric utilities have more choices to engage residential customers in DR programs [3]–[6]. The most commonly used is the time-based DR programs [1], [2], [6]–[10], in which demand reduction can be achieved in response to electricity prices. With regard to reliability of a power distribution system, incentive-based DR programs, such as emergency demand response programs (EDRP), are more desirable than time-based DR programs. Implementing EDRP, load reduction at customer premises is required when a power system is in stress conditions. One of the popular approaches among incentive-based DR programs is direct load control. With this approach, WHs [3] or AC compressors [5] at customer's premises can be remotely shut-off by utilities or demand response aggregators (DR AGG). This generally leads to customer loss of comfort and inconvenience. Currently, EDRP has been widely used at the transmission or sub-transmission levels where industrial or commercial load reduction can be achieved [11]–[13]. Nonetheless, there are very few publications that discuss EDRP implementation at a distribution level. Commercially, Siemens has released the demand response management system (DRMS) called surgical demand response. This system gives utilities an ability to selectively execute a demand curtailment at specific substations or feeder lines [14].

Gouveia *et al.* [15] proposed an EDRP that enables the use of residential load resources in response to contingencies in a distribution system. However, loads are modeled as lumped loads and characteristics of household appliances are not taken into account. The analytic hierarchy process-based DR strategy to alleviate power system stress conditions is presented in [16]. In this paper, to reduce the power demand at the TR level, the DL of all homes during a DR event is identical regardless of different homes' characteristics. There is a chance that unexpected impacts of an overly increased power demand following a DR event (i.e., demand restrike or DRK) can be experienced. Ying *et al.* [8] and Yoon *et al.* [17] suggested the approaches to tackle and mitigate impacts of DRK and reduce power demand during a DR event using dynamic pricing techniques. However, as the amount of load reduction cannot be guaranteed and depends heavily on customers' preferences, these approaches are undesirable. A customer reward scheme to shave peak demand is proposed in [18]. In this case, customers are paid based on load shift and voltage improvement during a DR event. Nevertheless, the load reshape insurance cannot be guaranteed as it relies heavily on homeowners' behaviors. This implies the method to handle DRK has not been fully studied.

Several approaches are proposed to overcome these negative impacts by controlling EV charging profiles at customer premises. Some approaches focus on centralized control where EVs are controlled from a central control center to maximize system load factor [19] or minimize system losses [20]. The others exploit decentralized control approaches where EV charging is controlled locally to minimize the requirement of communication infrastructure. These approaches mainly focus solely on controlling EV loads [21]–[23], while characteristics of other potentially controllable appliances are not considered.

Based on the literature search, there is still the lack of extensive studies on load reshape assurance at a TR level that gives end-use customers flexibility to control their appliances. In addition, adverse impacts of a DR event, e.g., transformer overload causing by a DRK, has not been addressed. To tackle these issues, this paper presents a decentralized control approach at a TR level and a home level that allows controlling household power-intensive appliances, including ACs, WH, clothes dryers (CD), and electric vehicles (EV). Critical loads, such as lighting loads, cooking, and plug loads, are not to control. The DR algorithm for the smart distribution transformer management (SDTM) is proposed with the objectives to: 1) ensure an instantaneous power demand at a TR below a certain DL level; 2) minimize the potential impacts of DRK at a TR; and 3) prevent or mitigate customer comfort violations.

This paper is organized as follows. The SDTM architecture is explained in Section II, the DR algorithm for the EDRP implementation at a TR level is proposed in Section III, the case study that showcases the effectiveness of the proposed DR algorithm is given in Section IV, simulation results and discussions are presented in Section V.

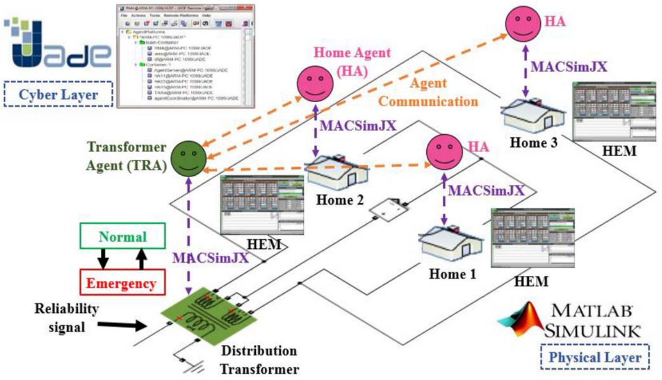

Fig. 1. Integrated system of the physical layer (a transformer, three homes, and DR-enabled appliances); and the cyber layer (MAS and HEM).

II. SDTM ARCHITECTURE

This paper focuses on implementing DR at a TR level, where a single-phase transformer (e.g., 25 kVA) serves several homes in the same neighborhood. The proposed design and architecture of the SDTM consists of two layers: 1) physical layer; and 2) cyber layer shown in Fig. 1. The physical layer is where real physical devices exist. This layer comprises a distribution network with a single-phase TR serving three homes (modeled in MATLAB/Simulink) and DR-enabled household appliances (modeled in the HEM environment [24]).

The cyber layer represents decision-making processes of the SDTM. This layer consists of the proposed MAS (developed using the java agent development framework [25] platform) and the HEM (stand-alone software developed in [24]). MAS comprises multiple distributed intelligent agents residing at their corresponding physical devices. The HEM is responsible for monitoring power consumption of DR-enabled household appliances and controlling appliance status during a DR event based on preset homeowner preferences. The middleware called MACSimJX [26] is used to link the MAS with the distribution network modeled in MATLAB/Simulink. The HEM is linked with the distribution network and its corresponding agent via TCP/IP communication. To enable real-world implementation of the proposed approach, a smart grid infrastructure that supports two-way communications between a TR and its connected homes is required; an example of which has been discussed in [27].

Although the SDTM architecture presented in this paper focuses mainly on the three-wire split-phase distribution system being widely used in the U.S., the proposed algorithm can be adopted for use with any network configurations. In terms of scalability, the proposed SDTM can be easily expanded to manage power demand at a distribution feeder level or at a distribution substation level. The power demand management goals during a DR event can be archived by the similar approach accounting for cable/line constraint, TR constraints as well as voltage level constraint, etc.

III. DEMAND RESPONSE ALGORITHM FOR SDTM

In this paper, it is assumed that a DR event has occurred and a DR AGG assigns a DL and a DR event duration (hours) to selected TRs. The overall objective of the proposed DR algorithm is to keep a total instantaneous power at a TR below a DL (kW) while impacts of DRK are mitigated. At a home level, homeowners have choices to decide which appliance to operate for how long. The proposed DR algorithm is devised and implemented at a TR level via a transformer agent (TRA), at the home level via a home agent (HA), and at the appliance level via an HEM.

A. TRAs Goals

A TRA located at a TR acts in pursuit of its goals by coordinating with HAs. TRAs objectives are as follows.

1) To keep a total instantaneous power demand at a TR (P_{TR}, kW) below a certain DL level during a DR event. This paper defines two operating states of a TR as "normal" and "emergency" based on the following constraints:

$$P_{\mathrm{TR}} = \sum_{i=1}^{N} P_{H,i} \leq \mathrm{Cap}_{\mathrm{TR}} \tag{1}$$

$$P_{\mathrm{TR}} \leq \mathrm{DL}_{\mathrm{AGG}\rightarrow\mathrm{TRA}} \tag{2}$$

where, $P_{H,i}$ is an instantaneous power demand of home $i \in N$. N is a number of homes served by a TR. $\mathrm{Cap}_{\mathrm{TR}}$ is a TRs loading capability. $\mathrm{DL}_{\mathrm{AGG}\rightarrow\mathrm{TRA}}$ is a DL (kW) given to a TRA by a DR AGG. A TR is in a normal operating state when none of the above constraints are violated; while it is in an emergency operating state when at least one constraint is violated. It should be noted that this paper is based on the assumption that the voltage level at a TR varies within an acceptable limit specified by ANSI C84.1 [28].

2) To minimize the demand restrike potential—a potential rebound power demand at a TR level ($\mathrm{DRKP}_{\mathrm{TR}}$, kWh). This is to mitigate impact of undesired new peak demand (DRK) at a TR after a DR event ends. The $\mathrm{DRKP}_{\mathrm{TR}}$ is mathematically defined as

$$\mathrm{DRKP}_{\mathrm{TR}} = \int_{t_{\mathrm{DR\_start}}}^{t_{\mathrm{DR\_end}}} (P_{\mathrm{TR,hist}} - P_{\mathrm{TR}})dt \tag{3}$$

where, $P_{\mathrm{TR,hist}}$ is a similar-day historical load profile of a TR during the same period as a DR event. $t_{\mathrm{DR\_start}}$ is a DR event start time. $t_{\mathrm{DR\_end}}$ is a DR event end time. As an actual required power demand of a TR during the same period as a DR event ($P_{\mathrm{TR},w/o\_\mathrm{DR}}$) is unknown, $P_{\mathrm{TR,hist}}$ is used with the assumption that homeowners maintain their typical behaviors for the same day type (weekday/weekend) with similar weather conditions. $\mathrm{DRKP}_{\mathrm{TR}}$ serves as a basis to estimate impacts of DRK as actual required power demands of homes might not be fulfilled during a DR event. Explicitly, some applicances might not be able to run as limited DL levels are imposed on homes.

B. HAs Goals

An HA acts in pursuit of homeowner's goals. If a homeowner participates in a DR program, an HA works cooperatively with its associated TRA in response to a DR event. In

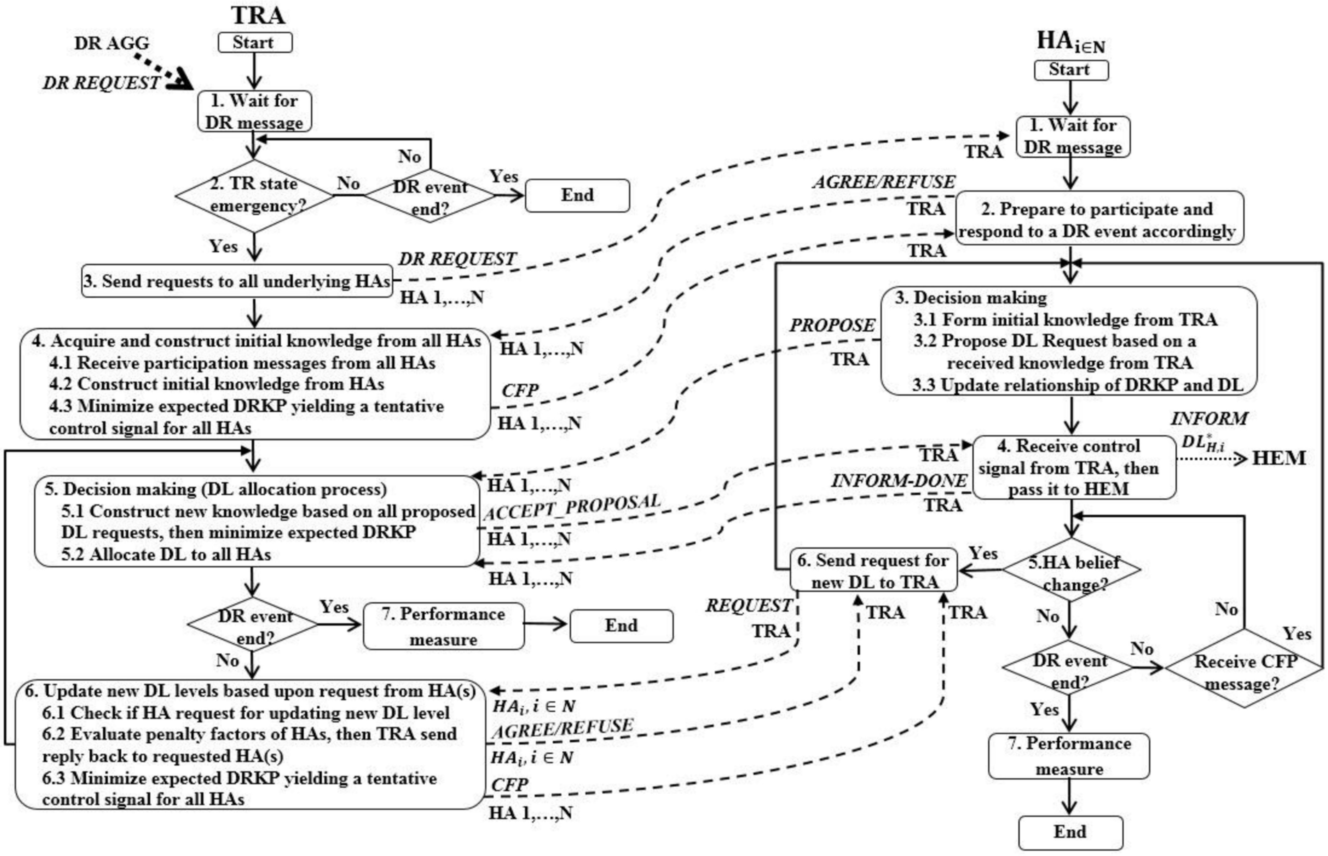

Fig. 2. Overall DR algorithm of a TRA resided at a TR and a HA resided at a home.

this paper, homeowner's goals are: 1) to ensure that critical loads (e.g., lighting loads, cooking, and plug loads) are served at all time; 2) to mitigate a homeowner's comfort level violation defined as deviations of room temperature and hot water temperature from their preset values; and 3) to minimize load compensation times of selected appliances due to delay from appliances rescheduling.

C. Overall DR Algorithm and Messaging Exchanges Between the TRA and HAs

The overall DR algorithm for a TRA and a HA is depicted in Fig. 2. Steps TRA1–TRA7 represent TRA algorithm. Steps HA1–HA7 represent HA algorithm. They work concurrently as follows.

Step TRA1: TRA waits for a DR *REQUEST* message from a DR AGG ($\mathbf{DL_{AGG\to TRA}}$) specifying an allocated DL and a DR event duration.

Step TRA2: TRA assesses a TR operating state. If it is normal, no action is taken. If it is emergency, TRA works with its associated HAs as follows.

Step TRA3: TRA sends DR *REQUEST* messages to all associated HAs notifying them a DR event.

Step HA1: HA waits for a DR *REQUEST* message.

Step HA2: HA responds to the TRA with either an *AGREE* or a *REFUSE* message. The message provides the TRA an initial knowledge of this HA: 1) electrical characteristic represents an electrical meter service ampere rating of a home ($\text{Amp\_Rating}_{H,i}$) and 2) DL request ($\text{DL}_{H,\text{req},i}$) is formed based on the objective of securing critical loads ($\text{DL}_{H,\text{req,lower},i}$) and mitigating customer comfort level violation ($\text{DL}_{H,\text{req,upper},i}$) given as

$$\text{DL}_{H,\text{req},i} \in \big[\text{DL}_{H,\text{req,lower},i} = P_{H,\text{hist,crit,max},i} \qquad \text{DL}_{H,\text{req,upper},i} = P_{H,\text{hist,max},i}\big] \quad (4)$$

where, $P_{H,\text{hist,crit,max},i}$ and $P_{H,\text{hist,max},i}$ are a maximum power demand of critical loads and a maximum power demand of total loads of a home based on similar-day historical data respectively; and 3) relationship $\text{DRKP}_{H,i}(\text{DL}_{H,i})$ between a demand restrike potential ($\text{DRKP}_{H,i}$) and a DL level ($\text{DL}_{H,i}$) of a home over a DR event period. This relationship is derived without the explicit knowledge from a TRA and the other neighboring HAs. The relationship is based on an average home's historical load profiles ($P_{H,\text{hist},i}$) of the same period, climate, and day of the week (weekday/weekend). By sampling different levels of $\text{DL}_{H,i}$ ranging from its upper bound ($\text{DL}_{H,\text{req,upper},i}$) to lower bound ($\text{DL}_{H,\text{req,lower},i}$) and applying it to (5), different values of $\text{DRKP}_{H,i}$ can be obtained

$$\text{DRKP}_{H,i} = \int_{t_{\text{DR}_\text{start}}}^{t_{\text{DR}_\text{end}}} \big(P_{H,\text{hist},i} - \text{DL}_{H,i}\big)dt \qquad \text{s.t. } P_{H,\text{hist},i} - \text{DL}_{H,i} \geq 0. \quad (5)$$

Using polynomial regression algorithm, an approximated $\text{DRKP}_{H,i}$ as a function of a $\text{DL}_{H,i}$ is empirically represented as a quadratic function (with $a_{H,i}$, $b_{H,i}$, and $c_{H,i}$ as coefficients) due to characteristics of the historical load profile of a home ($P_{H,\text{hist},i}$) [29] and a given $\text{DL}_{H,i}$ defined in

$$\text{DRKP}_{H,i}\left(\text{DL}_{H,i}\right) = a_{H,i} \cdot \text{DL}_{H,i}^{2} + b_{H,i} \cdot \text{DL}_{H,i} + c_{H,i}. \quad (6)$$

Step TRA4: TRA needs to acquire and construct initial knowledge based on information received from all HAs.

TRA4.1: The TRA receives *AGREE/REFUSE* messages from all associated HAs.

TRA4.2: TRA constructs initial knowledge about: 1) fair DL levels of all homes ($\mathbf{DL_{H,fair}}$) defined as

$$\mathbf{DL}_{\boldsymbol{H},\mathbf{fair}} = \left[\text{DL}_{H,\text{fair},1}, \ldots, \text{DL}_{H,\text{fair},N}\right]^{T} \quad (7)$$

$$\text{DL}_{H,\text{fair},i} = \frac{\mathbf{DL_{AGG \to TRA}} \times \text{Amp\_Rating}_{H,i}}{\sum_{i=1}^{N} \text{Amp\_Rating}_{H,i}}, \forall i \in N. \quad (8)$$

$\mathbf{DL}_{\boldsymbol{H},\mathbf{fair}}$ is defined as a vector containing fair DLs of all homes ($\text{DL}_{H,\text{fair},i}, \forall i \in N$) and 2) an expected demand restrike potential at a TR level ($\text{DRKP}_{\text{TR,exp}}$) that is calculated based on the relationship $\text{DRKP}_{H,i}(\text{DL}_{H,i})$ obtained in (6) from all associated HAs as follows:

$$\text{DRKP}_{\text{TR,exp}} = \sum_{i=1}^{N} \text{DRKP}_{H,i}(\text{DL}_{H,i}). \quad (9)$$

TRA4.3: TRA minimizes the $\text{DRKP}_{\text{TR,exp}}$ based on its initial knowledge (from Steps TRA4.1 and TRA4.2) to find a tentative DL level vector ($\mathbf{DL}_{\boldsymbol{H},\mathbf{ten}}$) for all HAs.

Objective function

$$\text{Min}\left(\text{DRKP}_{\text{TR,exp}} = \sum_{i=1}^{N}\left\{a_{H,i} \cdot \text{DL}_{H,\text{ten},i}^{2} + b_{H,i} \cdot \text{DL}_{H,\text{ten},i} + c_{H,i}\right\}\right) \quad (10)$$

subject to

Equality constraints

$$1) \sum_{i=1}^{N} \text{DL}_{H,\text{ten},i} = \text{DL}_{\text{AGG}\to\text{TRA}}.$$

Inequality constraints

$$2)\ \text{DL}_{H,\text{req,lower},i} \leq \text{DL}_{H,\text{ten},i} \leq \text{DL}_{H,\text{req,upper},i}, \forall i \in N$$

where, $\text{DL}_{H,\text{ten},i}$ is a tentative DL level of a home $i \in N$. Using Lagrange relaxation technique with Kuhn–Tucker conditions, TRA solves this nonlinear optimization problem given linear and bounded constraints yielding vector $\mathbf{DL}_{\boldsymbol{H},\mathbf{ten}}$

$$\mathbf{DL}_{\boldsymbol{H},\mathbf{ten}} = \left[\text{DL}_{H,\text{ten},1}, \ldots, \text{DL}_{H,\text{ten},N}\right]^{T}. \quad (11)$$

Then, the TRA sends CFP messages.

Step HA3: In this step, HA tries to minimize appliances' compensation time and to deploy $\text{DL}_{H,\text{fair},i}$ and $\text{DL}_{H,\text{ten},i}$ from a *CFP* message sent by a TRA. Pragmatically, required power demands of appliances are in discrete steps, the approximated $\text{DRKP}_{H,i}$ obtained from the initial knowledge of an HA in (6) does not decrease as $\text{DL}_{H,i}$ increases unless it is high enough to serve another appliance waiting to operate. Therefore, with additional knowledge from a TRA and its knowledge on current appliances' status, an HA updates the relationship $\text{DRKP}_{H,i}(\text{DL}_{H,i})$ in (6) as a piecewise linear function to obtain a more realistic behavior of $\text{DRKP}_{H,i}$. Intuitively, an HA will request for a suitable $\text{DL}_{H,i}$ level that it believes enough to serve its corresponding appliances. An HA also ensures that the requested $\text{DL}_{H,i}$ is not too high (with reference to its $\text{DL}_{H,\text{fair},i}$) during that time as an HA will be penalized by a TRA. The steps to obtain the new updated $\text{DL}_{H,\text{req},i}$ and $\text{DRKP}_{H,i}(\text{DL}_{H,i})$ are elaborated as follows.

HA3.1: HA acquires $\text{DL}_{H,\text{fair},i}$ and $\text{DL}_{H,\text{ten},i}$ from a *CFP* message sent by a TRA.

HA3.2: HA adjusts its $\text{DL}_{H,\text{req},i}$ in (4) to a vector $\mathbf{DL}_{\mathbf{H},\mathbf{req},\boldsymbol{i}}$ as explained in the Steps HA3.2.1 and HA3.2.2.

HA3.2.1: HA constructs its belief ($\mathbf{Belief}_{\boldsymbol{H},\boldsymbol{i}}$) vector defined in (12). This vector represents minimum required power demands (kW) based on all possible combinations of usage status of power-intensive appliances

$$[\mathbf{Belief}_{\boldsymbol{H},\boldsymbol{i}}]_{\boldsymbol{M}\mathbf{x1}} \in \mathbb{R}^{M} = [\mathbf{Comb}]_{\boldsymbol{M}\mathbf{x}\boldsymbol{C}} \cdot [\mathbf{Rated}]_{\boldsymbol{C}\mathbf{x1}} \quad (12)$$

where, $M = \sum_{k=1}^{C} C!/k!(C-k)!$ is a number of beliefs and C is a total number of appliances.

$[\mathbf{Comb}]_{\boldsymbol{M}\mathbf{x}\boldsymbol{C}}$ is a matrix of combinations of usage status of power-intensive appliances given as

$$[\mathbf{Comb}]_{\boldsymbol{M}\mathbf{x}\boldsymbol{C}} = \begin{bmatrix} s_{\text{app},1,1} & \cdots & s_{\text{app},1,C} \\ \vdots & \ddots & \vdots \\ s_{\text{app},M,1} & \cdots & s_{\text{app},M,C} \end{bmatrix} \quad (13)$$

$s_{\text{app},j\in M,k\in C}$ is a status of an appliance $k \in C$ in a belief $j \in M$ that can be either 0 or 1. Note that, for AC, the binary status of "0" means a thermostat mode is OFF; and the binary status of "1" means a thermostat is in either COOL or HEAT mode. For WH, CD, and EV binary status of 0 means OFF; and binary status of 1 means ON.

$[\mathbf{Rated}]_{\boldsymbol{C}\mathbf{x1}}$ is a vector containing rated power demands (kW) of C appliances given as

$$[\mathbf{Rated}]_{\boldsymbol{C}\mathbf{x1}} = \left[\text{Rated}_{\text{app},1}, \ldots, \text{Rated}_{\text{app},C}\right]^{T}. \quad (14)$$

$\text{Rated}_{\text{app},k\in C}$ is a rated power demand (kW) of a power-intensive appliance $k \in C$.

HA3.2.2: HA updates $\text{DL}_{H,\text{req},i}$ as a vector $\mathbf{DL}_{\boldsymbol{H},\mathbf{req},\boldsymbol{i}}$ according to the $\text{DL}_{H,\text{fair},i}$, $\text{DL}_{H,\text{ten},i}$, and $\mathbf{Belief}_{\boldsymbol{H},\boldsymbol{i}}$ using the decision criteria explained below.

Step 1: From the reordered $\mathbf{Belief}_{\boldsymbol{H},\boldsymbol{i}}$ vector from min to max value, find $\text{Belief}_{H,i,j} = \max(\text{Belief}_{H,i,k} \in \mathbf{Belief}_{\boldsymbol{H},\boldsymbol{i}})$; s.t. $\text{Belief}_{H,i,k} + P_{H,\text{hist,crit,max},i} \leq \text{DL}_{H,\text{ten},i}$.

Step2: Start from the element $\text{Belief}_{H,i,j}$ from Step 1, a vector $\mathbf{DL}_{\mathbf{H},\mathbf{req},\boldsymbol{i}}$ is obtained based on the following conditions: if $\text{Belief}_{H,i,j+1} + P_{H,\text{hist,crit,max},i} \geq \text{DL}_{H,\text{fair},i}$, then:

$$\mathbf{DL}_{\boldsymbol{H},\mathbf{req},\boldsymbol{i}} = \begin{bmatrix} \text{DL}_{H,\text{req}}^{1} = \text{Belief}_{H,i,j} + P_{H,\text{hist,crit},90\%,i} \\ \text{DL}_{H,\text{req}}^{2} = \text{Belief}_{H,i,j} + P_{H,\text{hist,crit,max},i} \\ \text{DL}_{H,\text{req}}^{3} = \text{Belief}_{H,i,j+1} + P_{H,\text{hist,crit},90\%,i} \\ \text{DL}_{H,\text{req}}^{4} = \text{Belief}_{H,i,j+1} + P_{H,\text{hist,crit,max},i} \end{bmatrix}. \quad (15)$$

Otherwise

$$\begin{aligned}\mathbf{DL}_{\boldsymbol{H},\mathbf{req},\boldsymbol{i}} &= \begin{bmatrix} \mathrm{DL}^{1}_{H,\mathrm{req}} & \mathrm{DL}^{2}_{H,\mathrm{req}} & \mathrm{DL}^{3}_{H,\mathrm{req}} & \mathrm{DL}^{4}_{H,\mathrm{req}} \end{bmatrix}^{T} \\ &= \begin{bmatrix}1\ 1\ 1\ 1\end{bmatrix}^{T} \cdot \begin{bmatrix}\mathrm{Belief}_{H,i,j+1} + P_{H,\mathrm{hist,crit,max}}\end{bmatrix}\end{aligned} \tag{16}$$

where, $P_{H,\mathrm{hist,crit},90\%,i}$is the power demand level (kW) of a home $i \in N$ in which an hourly-average of critical loads will not exceed for 90% of the time. It can be obtained from the historical load duration of curve of critical loads of a home forming from the same period as a DR event. Regarding the second condition, as HA knows its own $\mathrm{DL}_{H,\mathrm{fair},i}$, it will try to get a highest DL allowance as possible [shown in (16)] so that impacts of DRK tend to be minimal to the homeowners.

HA3.3: After getting the $\mathbf{DL}_{\boldsymbol{H},\mathbf{req},\boldsymbol{i}}$ from HA3.2, an HA updates the relationship $\mathrm{DRKP}_{H,i}(\mathrm{DL}_{H,i})$ in (6) as a piecewise linear function shown in the following:

$$\begin{aligned}&\mathrm{DRKP}_{H,i}(\mathrm{DL}_{H,i}) \\ &\quad = \begin{cases} m_1 \triangle x_1 + \mathrm{DRKP}^{1}_{H} \text{ if } \mathrm{DL}^{1}_{H,\mathrm{req}} \leq \mathrm{DL}_{H,i} < \mathrm{DL}^{2}_{H,\mathrm{req}} \\ \mathrm{DRKP}^{2}_{H} \text{ if } \mathrm{DL}^{2}_{H,\mathrm{req}} \leq \mathrm{DL}_{H,i} \leq \mathrm{DL}^{3}_{H,\mathrm{req}} \\ m_2 \triangle x_2 + \mathrm{DRKP}^{2}_{H} \text{ if } \mathrm{DL}^{3}_{H,\mathrm{req}} < \mathrm{DL}_{H,i} \leq \mathrm{DL}^{4}_{H,\mathrm{req}} \end{cases}\end{aligned} \tag{17}$$

$$m_1 = \frac{\mathrm{DRKP}^{2}_{H} - \mathrm{DRKP}^{1}_{H}}{\mathrm{DL}^{2}_{H,\mathrm{req}} - \mathrm{DL}^{1}_{H,\mathrm{req}}}, \triangle x_1 = \mathrm{DL}_{H,i} - \mathrm{DL}^{1}_{H,\mathrm{req}} \tag{18}$$

$$m_2 = \frac{\mathrm{DRKP}^{3}_{H} - \mathrm{DRKP}^{2}_{H}}{\mathrm{DL}^{4}_{H,\mathrm{req}} - \mathrm{DL}^{3}_{H,\mathrm{req}}}, \triangle x_2 = \mathrm{DL}_{H,i} - \mathrm{DL}^{3}_{H,\mathrm{req}} \tag{19}$$

$$\mathrm{DRKP}^{1}_{H} = a_{H,i} \cdot \left(\mathrm{DL}^{1}_{H,\mathrm{req}}\right)^{2} + b_{H,i} \cdot \left(\mathrm{DL}^{1}_{H,\mathrm{req}}\right) + c_{H,i} \tag{20}$$

$$\mathrm{DRKP}^{2}_{H} = \left(\sum_{k=2}^{3}\left(a_{H,i} \cdot \left(\mathrm{DL}^{k}_{H,\mathrm{req}}\right)^{2} + b_{H,i} \cdot \left(\mathrm{DL}^{k}_{H,\mathrm{req}}\right) + c_{H,i}\right)\right)\Big/2 \tag{21}$$

$$\mathrm{DRKP}^{3}_{H} = a_{H,i} \cdot \left(\mathrm{DL}^{4}_{H,\mathrm{req}}\right)^{2} + b_{H,i} \cdot \left(\mathrm{DL}^{4}_{H,\mathrm{req}}\right) + c_{H,i} \tag{22}$$

where, $a_{H,i}, b_{H,i}$, and $c_{H,i}$ are obtained from (6) in order to estimate DRKP^{1}_{H}, DRKP^{2}_{H}, and DRKP^{3}_{H} of the function $\mathrm{DRKP}_{\boldsymbol{H},\boldsymbol{i}}(\mathrm{DL}_{H,i})$ based on the vector $\mathbf{DL}_{\boldsymbol{H},\mathbf{req},\boldsymbol{i}}$. Then an HA send a *PROPOSE* message with the updated $\mathbf{DL}_{\boldsymbol{H},\mathbf{req},\boldsymbol{i}}$ and $\mathrm{DRKP}_{H,i}(\mathrm{DL}_{H,i})$ to a TRA.

Step TRA5: Once $\mathbf{DL}_{\boldsymbol{H},\mathbf{req},\boldsymbol{i}}$ and $\mathrm{DRKP}_{H,i}(\mathrm{DL}_{H,i})$ of all participated HAs are updated, the TRA finds the optimal DL levels ($\mathbf{DL}^{*}_{\boldsymbol{H}}$) in which the TRA and HAs mutually agree that the expected demand restrike potential at a TR level ($\mathrm{DRKP}_{\mathrm{TR,exp}}$) after a DR event will be minimal.

TRA5.1: After receiving all *PROPOSE* messages, the TRA constructs its new knowledge by forming a new optimization problem. The objective function of the TRA is to minimize $\mathrm{DRKP}_{\mathrm{TR,exp}}$ at a transformer level

$$\mathrm{Min}\ \ \mathrm{DRKP}_{\mathrm{TR,exp}} = \mathrm{Min}\left(\sum_{i=1}^{N}\mathrm{DRKP}_{H,i}\left(\mathrm{DL}^{*}_{H,i}\right)\right) \tag{23}$$

subject to

Equality constraints

1) $\sum_{i=1}^{N}\mathrm{DL}^{*}_{H,i} = \mathrm{DL}_{\mathrm{AGG}\rightarrow\mathrm{TRA}}$.

Inequality constraints

2) $\mathrm{DL}^{1}_{H,\mathrm{req}} \leq \mathrm{DL}^{*}_{H,i} \leq \mathrm{DL}^{4}_{H,\mathrm{req}}, \forall i \in N$.

3) $\mathrm{DL}_{H,\mathrm{req,lower},i} \leq \mathrm{DL}^{*}_{H,i} \leq \mathrm{DL}_{H,\mathrm{req,upper},i}, \forall i \in N$

where, $\mathrm{DL}^{*}_{H,i}$ is an optimal DL level given to a home $i \in N$. Using dual upper bounding linear programming, the TRA solves this linear optimization problem given piecewise linear objective function and linear and bounded constraints. This yields a DL control signal vector: $\mathbf{DL}^{*}_{\boldsymbol{H}} = [\mathrm{DL}^{*}_{H,1} \ldots \mathrm{DL}^{*}_{H,N}]^{T}$.

TRA5.2: TRA allocates $\mathbf{DL}^{*}_{\boldsymbol{H}}$ by sending *ACCEPT_PROPOSAL* messages to all HAs. Then, the TRA receives *INFORM_DONE* messages indicating that all participating HAs have already received the $\mathbf{DL}^{*}_{\boldsymbol{H}}$ and deployed the DL control signals at their corresponding HEMs.

Step HA4: HA receives a DL control signal ($\mathrm{DL}^{*}_{H,i}$). Then, it passes the signal to an HEM. Finally, an HA sends back an *INFORM_DONE* message for successful confirmation.

Step HA5: During a DR event, an HA will periodically update its belief due to a change in run-time schedule of power-intensive appliances. These changes can result from a newly plugged-in appliance (e.g., EV is plugged in), or a condition that leads to customer comfort violations. If the HA belief ($\mathbf{Belief}_{\boldsymbol{H},\boldsymbol{i}}$) changes during a DR event, it will request a TRA for a new DL as stipulated in Step HA6, otherwise it will check whether or not a DR event has already ended. After a DR event has already ended, an HA will stop its services and evaluate its performance by carrying out the performance measure described in Step HA7. If it has not, the HA will again check whether or not it receives a CFP message from a TRA as a result of a request to update $\mathbf{DL}^{*}_{\boldsymbol{H}}$ sent by another HA. If the HA receives a CFP message, it sends a *PROPOSE* message back to the TRA as explained in Step HA3.

Step HA6: HA sends a *REQUEST* message to let the TRA know that it needs to update its DL level due to a change in appliances' run-time schedule. If the HA receives an *AGREE* message, it constructs a new knowledge from the received CFP message. Then, the HA sends a *PROPOSE* message back to a TRA as explained in Step HA3.

Step TRA6: TRA updates $\mathbf{DL}^{*}_{\boldsymbol{H}}$ based upon the request from an HA to update its current $\mathrm{DL}^{*}_{H,i}$.

TRA6.1: TRA receives a *REQUEST* message from one or more HA asking to change its DL level ($\mathrm{DL}^{*}_{H,i}$).

TRA6.2: TRA makes the decision to accept/reject the request by evaluating the $\mathbf{PF}_{\boldsymbol{H}}$ and the newly requested for $\mathrm{DL}^{*}_{H,i}$ from an HA_{i}, $i \in N$ as follows.

TRA6.2.1: To ensure fairness in distributing $\mathrm{DL}_{\mathrm{AGG}\rightarrow\mathrm{TRA}}$, the TRA evaluates homes' penalty factors ($\mathbf{PF}_{\boldsymbol{H}}$). Each element $\mathrm{PF}_{H,i}$ of $\mathbf{PF}_{\boldsymbol{H}} = [\mathrm{PF}_{H,1} \ldots \mathrm{PF}_{H,N}]^{T}$ defined in (24) is a penalty factor imposed on a home $i \in N$

$$\mathrm{PF}_{H,i} = \begin{cases} 1 \text{ if } \left(\int_{t_{\mathrm{DR\_start}}}^{t_{\mathrm{eval}}} \mathrm{DL}^*_{H,i} dt - \int_{t_{\mathrm{DR\_start}}}^{t_{\mathrm{eval}}} \mathrm{DL}_{H,\mathrm{fair},i} dt\right) < 0 \\ 0 \text{ if } \left(\int_{t_{\mathrm{DR\_start}}}^{t_{\mathrm{eval}}} \mathrm{DL}^*_{H,i} dt - \int_{t_{\mathrm{DR\_start}}}^{t_{\mathrm{eval}}} \mathrm{DL}_{H,\mathrm{fair},i} dt\right) = 0 \quad \forall i \in N \\ -1 \text{ if } \left(\int_{t_{\mathrm{DR\_start}}}^{t_{\mathrm{eval}}} \mathrm{DL}^*_{H,i} dt - \int_{t_{\mathrm{DR\_start}}}^{t_{\mathrm{eval}}} \mathrm{DL}_{H,\mathrm{fair},i.} dt\right) > 0 \end{cases} \tag{24}$$

where, t_{eval} is a time that a TRA evaluates $\mathbf{PF}_{\boldsymbol{H}}$ as soon as it receives a request from an HA. The $\mathrm{PF}_{H,i}$ (either −1, 0, or 1) of a home $i \in N$ is determined based on $\mathrm{DL}^*_{H,i}$ as compared to $\mathrm{DL}_{H,\mathrm{fair},i}$ in terms of energy consumption over time. This term implies an average of $\mathrm{DL}^*_{H,i}$ that an HA receives of from $t_{\mathrm{DR\_start}}$ to t_{eval}. $\mathbf{PF_H}$ is used as a decision criteria whether or not the TRA will update $\mathbf{DL}^*_{\boldsymbol{H}}$ being requested by an HA.

TRA6.2.2: TRA will send *AGREE* messages all participated HAs based on the following conditions.

1) $\mathrm{PF}_{H,i} = 1$, and an HA requests a higher or lower DL level. This because the average of its received $\mathrm{DL}^*_{H,i}$ is lower than its fair DL ($\mathrm{DL}_{H,\mathrm{fair},i}$).
2) $\mathrm{PF}_{H,i} = 0$ or -1, an HA can only ask for a lower DL level because the average of its received $\mathrm{DL}^*_{H,i}$ is the same ($\mathrm{PF}_{H,i} = 0$) or higher ($\mathrm{PF}_{H,i} = -1$) than its fair DL ($\mathrm{DL}_{H,\mathrm{fair},i}$).

   The TRA will sends a *REFUSE* message back to the requested HA based on the following condition. Then, the TRA stops the process of updating $\mathrm{DL}^*_{H,i}$ of the requested HA.
3) $\mathrm{PF}_{H,i} = 0$ or -1, an HA asks for a higher DL level because the average of its received $\mathrm{DL}^*_{H,i}$ is the same ($\mathrm{PF}_{H,i} = 0$) or higher ($\mathrm{PF}_{H,i} = -1$) than its fair DL ($\mathrm{DL}_{H,\mathrm{fair},i}$) at the time the $\mathbf{PF_H}$ is evaluated.

TRA6.3: TRA minimizes a $\mathrm{DRKP}_{\mathrm{TR,exp}}$ as explained in Step TRA4.3 given the updated inequality constraint on the $\mathrm{DL}_{H,i,\mathrm{ten}}$ of the requested HA as follows:

$PF_{H,i}$	$Request$	updated constraint on $DL_{H,ten,i}$
1	higher $DL^*_{H,i}$	$DL^*_{H,i} < DL_{H,ten,i} \leq DL_{H,req,upper,i}$
1, 0, -1	lower $DL^*_{H,i}$	$DL_{H,req,lower,i} \leq DL_{H,ten,i} \leq DL^*_{H,i}$

.

Where, $\mathrm{DL}^*_{H,i}$ is the currently received DL of an HA before it requests for a new DL level. Therefore, a new $\mathbf{DL}_{\boldsymbol{H},\mathbf{ten}} = [\mathrm{DL}_{H,\mathrm{ten},1} \ldots \mathrm{DL}_{H,\mathrm{ten},N}]^T$ for all HAs is obtained. Finally, the TRA sends CFP messages to all participated HAs. Then, the TRA proceeds to update a $\mathbf{DL}^*_{\boldsymbol{H}}$ based upon the DL allocation process explained in Step TRA5.

Step TRA7: After a DR event ends, a TRA assesses its performance as follows.

TRA7.1: TRA calculates the power exceed DL (PEDL) index. If PEDL is greater than zero, it means that a power demand of a TR (P_{TR}) exceeds a given $\mathrm{DL}_{\mathrm{AGG}\to\mathrm{TRA}}$ during a DR event

$$\mathrm{PEDL} = \int_{t_{\mathrm{DR\_start}}}^{t_{\mathrm{DR\_end}}} (P_{\mathrm{TR}} - \mathrm{DL}_{\mathrm{AGG}\to\mathrm{TR}})dt$$
$$\text{s.t.} \quad P_{\mathrm{TR}} - \mathrm{DL}_{\mathrm{AGG}\to\mathrm{TR}} \geq 0. \tag{25}$$

TRA7.2: The TRA assesses its performance on minimizing $\mathrm{DRKP}_{\mathrm{TR}}$ by evaluating an actual load profile of a TR during a DR event (P_{TR}) compared with its historical load profile without a DR event ($P_{\mathrm{TR,hist}}$) during the same period yielding the index $\mathrm{DRKP}_{\mathrm{TR,act}}$ defined in (26). The smaller $\mathrm{DRKP}_{\mathrm{TR,act}}$, the lower impacts of DRK can be expected

$$\mathrm{DRKP}_{\mathrm{TR,act}} = \int_{t_{\mathrm{DR\_start}}}^{t_{\mathrm{DR\_end}}} (P_{\mathrm{TR,hist}} - P_{\mathrm{TR,act}})dt. \tag{26}$$

Step HA7: After a DR event ends, an HA assesses its performance as follows.

HA7.1: HA calculates the DL below critical loads (DLBCL) index. If DLBCL is greater than zero the critical loads are violated during a DR event

$$\mathrm{DLBCL} = \int_{t_{\mathrm{DR_{start}}}}^{t_{\mathrm{DR_{end}}}} \left(P_{H,\mathrm{hist,max},i} - \mathrm{DL}^*_{H,i}\right) dt$$
$$\text{s.t.} \quad P_{H,\mathrm{hist,max},i} - \mathrm{DL}^*_H(t) \geq 0. \tag{27}$$

HA7.2: HA calculates CLV index defined as follows:

$$\begin{aligned} CLV = & \int_{t_{\mathrm{DR\_start}}}^{t_{\mathrm{DR\_end}}} (\mathrm{temp_{room}} - \mathrm{temp_{AC,set}})\, dt \\ & + \int_{t_{\mathrm{DR\_start}}}^{t_{\mathrm{DR\_end}}} (\mathrm{temp_{water}} - \mathrm{temp_{WH,set}})\, dt \\ \text{s.t.} \quad & \left|\mathrm{temp_{room}} - \mathrm{temp_{AC,set}}\right| > \mathrm{temp_{AC,deadband}} \\ & \left|\mathrm{temp_{water}} - \mathrm{temp_{WH,set}}\right| > \mathrm{temp_{WH,deadband}} \end{aligned} \tag{28}$$

where, $\mathrm{temp_{room}}$ is a room temperature profile during a DR event; $\mathrm{temp_{AC,set}}$ is a room temperature set point of an AC; $\mathrm{temp_{AC,deadband}}$ is an AC temperature deadband; $\mathrm{temp_{water}}$ is a hot water temperature profile during a DR event; $\mathrm{temp_{WH,set}}$ is a hot water temperature set point of a WH; $\mathrm{temp_{WH,deadband}}$ is a WH temperature deadband. CLV index of a home calculated at the end of a DR event (CLV_{DRevent}) is compared to CLV index calculated at the same time period where there is no DR event (CLV_{w/o_DR}). If a CLV_{DRevent} is not comparable with a CLV_{w/o_DR}, a customer's comfort level during a DR event is violated.

HA7.3: An HA assesses its performance on minimizing appliances' operating times by evaluating an actual demand restrike potential, $\mathrm{DRKP}_{H,\mathrm{act},i}$, as follows:

$$\mathrm{DRKP}_{H,\mathrm{act},i} = \int_{t_{\mathrm{DR\_start}}}^{t_{\mathrm{DR\_end}}} (P_{H,\mathrm{hist},i} - P_{H,i})dt \tag{29}$$

where, $P_{H,i}$ is an actual power demand of a home $i \in N$ (kW) during a DR event.

D. Algorithms at Appliance Level

After an HA receives a control signal $\mathrm{DL}^*_{H,i}$, it passes the signal to the corresponding HEM. According to our previously proposed HEM algorithms [19], the HEM works to ensure that an instantaneous power demand at home will not exceed the given DL $\mathrm{DL}^*_{H,i}$ during a DR event. The HEM communicates and sends control signals to allow rescheduling operation of power-intensive appliances according to homeowner's preference. The delay account for the operating interval of the HEM is in 1-min interval.

TABLE I
TR ATTRIBUTES AND DR EVENT

Attribute	Value	Attribute	Value
Rating	25 kVA	Operating state	Normal
Voltage ratio	7.2kV/120 /240V	DR event	Occur at 17:10 until 19:00
Loading capability	~ 25 kW	$DL_{AGG\to TRA}$	16 kW

TABLE II
HOME ATTRIBUTES AND HOMEOWNER PREFERENCE SETTINGS

	Home 1 (HA1,HEM1)	Home 2 (HA2,HEM2)	Home 3 (HA3,HEM3)
Home parameters:			
Size	1,833 ft^2	2,559 ft^2	1,310 ft^2
Elec. meter service amp	150 A	200 A	100 A
Appliances ratings and homeowner preference setting:			
1. Air Conditioner (AC)	Priority #1		
1.1 Rating 1.2 Temp set point 1.3 Start time	1.92 kW 76 ± 2 F° Before 17:00	2.60 kW 74 ± 2 F° Before 17:00	1.92 kW 76 ± 2 F° After 17:40
2. Water Heater (WH)	Priority #2		
2.1 Rating 2.2 Temp set point	3.80 kW 110 ± 10 F°	4.50 kW 120 ± 10 F°	3.80 kW 115 ± 10 F°
3. Clothes Dryer (CD)	Priority #3		
3.1 Rating (heat/motor) 3.2 Start time 3.3 Required run time	2.88/0.18 kW 17:00 60 min	4.90/0.377 kW 16:50 60 min	2.88/0.18 kW - -
4. Electric Vehicle (EV)	Priority #4		
4.1 Rating 4.2 Start time 4.3 Required run time	3.3 kW 17:05 200 min	3.3 kW 16:30 145 min	3.3 kW 17:45 180 min
5. Household load	Note: CL = critical loads; HH = household loads		
5.1 Max CL during DR 5.2 Max HH during DR	0.52 kW 8.29 kW	1.82 kW 11.26 kW	0.52 kW 3.82 kW

IV. CASE STUDY DESCRIPTION

The proposed case study of the SDTM contains a TR serving three homes. Each home has an HEM that allows automated scheduling of power-intensive appliances. Tables I and II summarize attributes of the TR and homes under study respectively.

V. SIMULATION RESULTS AND DISCUSSION

To assess the effectiveness of the proposed DR algorithm, this section compares the simulation result of the proposed DR algorithm with the result of the simple DR algorithm.

A. Simulation Results of the Proposed DR Algorithm

The simulation result of the proposed DR algorithm is shown in Fig. 3 for the TR and Figs. 4–6 for the homes 1–3, respectively. The chronology of the events during a DR period is discussed in detail below.

At 17:10 h, after receiving the DR event signal ($\mathrm{DL}_{\mathrm{AGG}\to\mathrm{TR}}$), TRA takes no action since the transformer is in its normal operating state.

At 17:26 h (①), the TRA is in emergency state (P_{TR} is higher than $\mathrm{DL}_{\mathrm{AGG}\to\mathrm{TR}}$). The TRA, then, starts to work with participating HAs according to the proposed DR algorithm. After the DL allocation processes, the TRA allocates $\mathbf{DL}_H^*$ of 6.72, 6.81, and 2.47 kW to HAs 1, 2, and 3, respectively based on the TRA belief on the $\mathrm{DRKP}_{\mathrm{TR}}$ and HAs' beliefs on their power demand requirements.

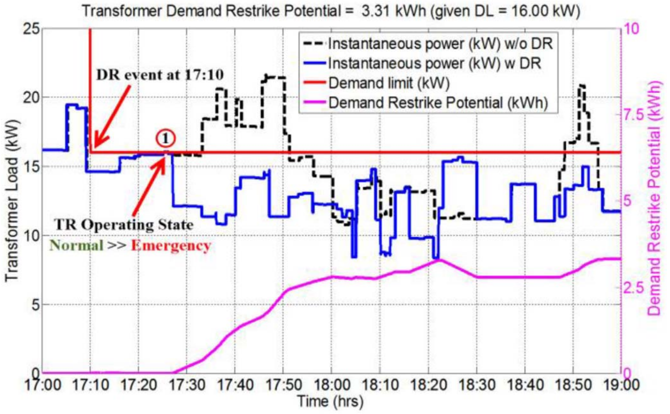

Fig. 3. Simulation results of the proposed DR algorithm at the transformer.

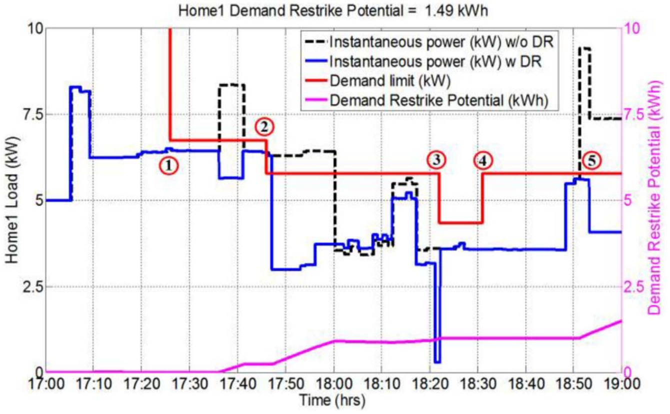

Fig. 4. Simulation results of the proposed DR algorithm at home 1.

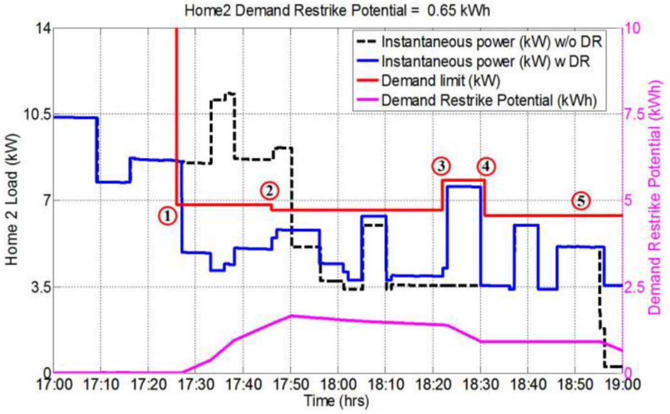

Fig. 5. Simulation results of the proposed DR algorithm at home 2.

At 17:45 h (②), HA3 requests the TRA for a higher DL as its belief changes due to the homeowner has just arrived home and plugged in his EV. Since the average DL that the HA3 currently received is lower than its fair DL, the TRA reallocate $\mathbf{DL}_H^*$ of 5.76, 6.60, and 3.64 kW to homes 1–3, respectively. Noticeably, the time that the EV is charged is around 17:50 h due to the higher-priority AC is still in operation at the time the HEM3 receives DL and is turned OFF at around 17:50 h.

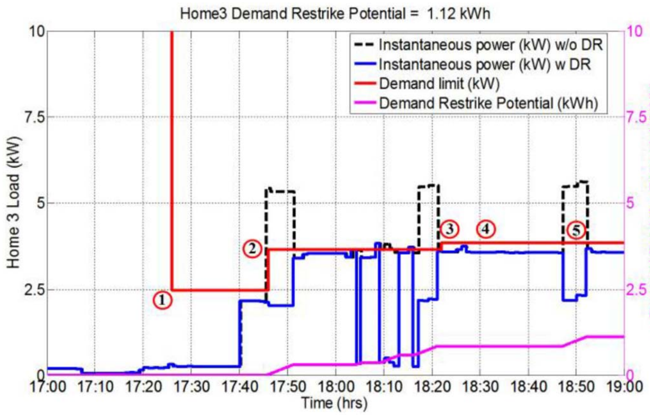

Fig. 6. Simulation results of the proposed DR algorithm at home 3.

Notice that the power demand of home 1 at ② and home 2 at ① decrease 1 min after HEM1 and HEM2 receives the DL. This delay accounts for the operating interval of HEM, which is in 1-min interval.

At 18:20 h (③), HA1 requests the TRA for a lower DL as its belief changes due to the CD has finished its operation. The TRA reallocate $\mathbf{DL}_H^*$ of 4.34, 7.81, and 3.85 kW to HAs 1–3, respectively.

At 18:29 h (④), HA2 requests the TRA for a lower DL as its belief changes due to the CD has finished its operation. The TRA reallocates $\mathbf{DL}_H^*$ of 5.76, 6.39, and 3.85 kW to HAs 1–3, respectively.

At 18:51 h (⑤), HA1 requests the TRA for a higher DL as its belief changes due to the WH starts to operate as a result of hot water temperature drops below the preset value. Since the average DL that HA1 currently received is higher than its fair DL, the TRA retains the current DL allocation. However, according to the load priority preference setting of home 1, the WH is turned on resulting in EV charging being on hold.

According to Fig. 3, the transformer load profile with DR (P_{TR}) is kept below the given $\mathrm{DL}_{\mathrm{AGG}\rightarrow\mathrm{TR}}$ during the DR event. The TRAs PEDL index is nearly zero. The assessed demand restrike potential of the transformer ($\mathrm{DRKP}_{\mathrm{TR}}$) is 3.31 kWh. This can be considered as equivalent to a 3.31 kW increase in the transformer load for 1 h due to load compensation of deferred appliances. In addition, the instantaneous power demand of all homes are controlled below the allocated $\mathbf{DL}_H^*$ (Figs. 4–6). According to the HAs' performance measures, all DLBCL indexes are zero as critical loads of all homes are served during the DR event. Customer comfort levels are also not violated as all homes' CLV_{DRevent} are less than 1% different to their CLV_{w/o_DR}. This implies ACs and WHs operations are not affected by the DR event. Table III summarizes the actual demand restrike potential ($\mathrm{DRKP}_{H,\mathrm{act},i}$) of each home and the delayed completion times of CD/EV, which represent additional time required for CD/EV to finish its operation as compared to its original schedule.

TABLE III
SIMULATION RESULTS SUMMARY OF THE PROPOSED DR STRATEGY

	Home 1	Home 2	Home 3
$DRKP_{H,act,i}$	1.49 kWh	0.65 kWh	1.12 kWh
CD delayed completion time	20 minutes	39 minutes	-
EV delayed completion time	26 minutes	26 minutes	20 minutes

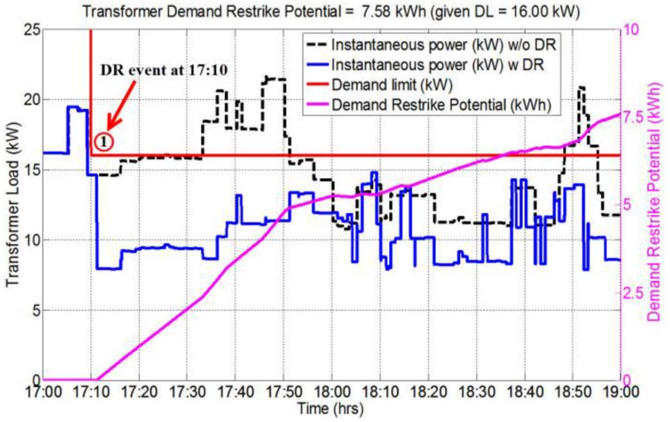

Fig. 7. Simulation results of the simple DR strategy at the transformer.

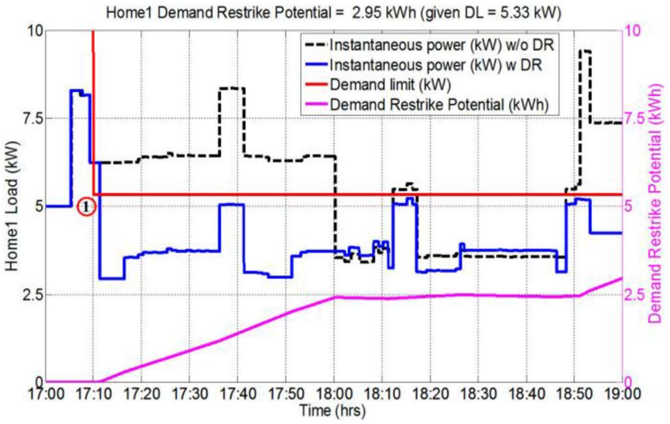

Fig. 8. Simulation results of the proposed DR strategy at home 1.

B. Simulation Results of the Simple DR Algorithm

The simple DR algorithm is chosen based on the fact that EDRP are not widely used at a distribution level, and most electric utilities have little knowledge on homes' characteristics. Accounting for this, rather than allocating the same DL to all homes as in [16], this paper implements the simple DR algorithm that allocates a fixed fair DL during a DR event based on homes' electrical meter service ampere ratings defined in (8).

The simulation results of the simple DR algorithm are shown in Fig. 7 for the TR and Figs. 8–10 for the homes 1–3, respectively. The chronology of events during a DR event is elaborated as: after receiving the DR event signal ($\mathrm{DL}_{\mathrm{AGG}\rightarrow\mathrm{TR}}$) with 16 kW DL from 17:10 to 19:00 h at ①, the TRA immediately allocates fair DLs based on the homes' electrical meter service ampere ratings. These are 5.33, 7.11, and 3.56 kW for HAs1–3, respectively. These DL are retained until the DR event ends.

According to Fig. 7, the total instantaneous power at the transformer (P_{TR}) is kept below the given $\mathrm{DL}_{\mathrm{AGG}\rightarrow\mathrm{TR}}$ during the DR period (the TRAs PEDL index is zero).

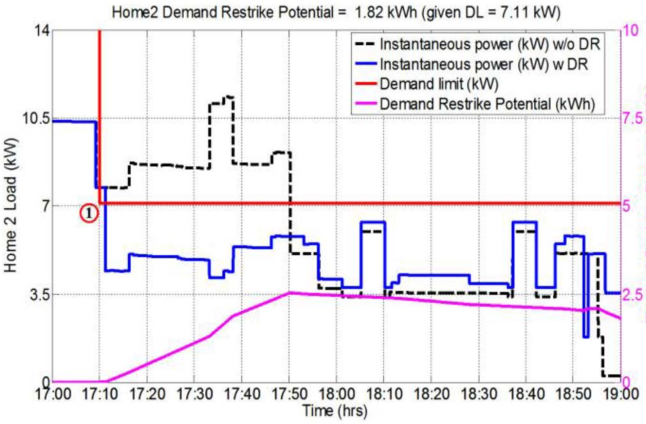

Fig. 9. Simulation results of the proposed DR strategy at home 2.

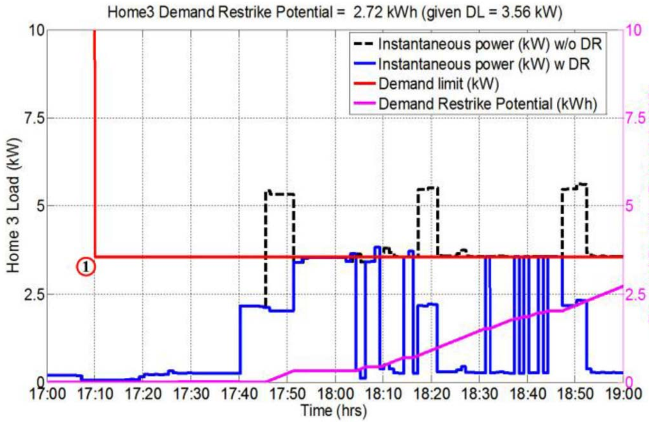

Fig. 10. Simulation results of the proposed DR strategy at home 3.

TABLE IV

SIMULATION RESULTS SUMMARY OF THE SIMPLE DR STRATEGY

	Home 1	Home 2	Home 3
$DRKP_{H,act,i}$	2.95 kWh	1.82 kWh	2.72 kWh
CD delayed completion time	68 minutes	61 minutes	-
EV delayed completion time	49 minutes	45 minutes	49 minutes

The assessed demand restrike potential of the transformer ($\mathrm{DRKP}_{\mathrm{TR}}$) is 7.58 kWh. This can be considered as equivalent to a 7.58 kW increase in a load of the transformer for 1 h due to load compensation of appliances that have been deferred. This can cause an undesired transformer overload condition as well as undervoltage problem as the impacts of DRK following a DR event. Nevertheless, the instantaneous power consumption of all three homes are controlled below the allocated $\mathbf{DL}_{\boldsymbol{H}}^{*}$ (Figs. 8–10) without violating their critical loads levels (all DLBCL indexes are zero) and their comfort level preferences (all homes' CLV_{DRevent} are less than 1% different to their CLV_{normal}). Table IV summarizes the actual demand restrike potential ($\mathrm{DRKP}_{H,\mathrm{act},i}$) of each home and the delayed completion time of CD and EV.

C. Simulation Results Discussion

Considering performance measures of the TRA and HAs, the proposed DR algorithm considerably reduce the demand restrike potential both at the transformer level ($\mathrm{DRKP}_{\mathrm{TR}}$) and the home level ($\mathrm{DRKP}_{H,i}$) as compared to the simple DR algorithm. The assessed $\mathrm{DRKP}_{\mathrm{TR}}$ of the transformer is 3.31 kWh with the proposed DR algorithm representing 56% reduction compared to the 7.58 kWh $\mathrm{DRKP}_{\mathrm{TR}}$ with the simple DR algorithm. The lesser the demand restrike potential at the transformer level implies the lesser the chance that an overload condition at the transformer occurs following a DR event. At the home level, it can be seen that the delayed completion time of scheduled appliances (CDs and EVs) are substantially reduced as well as the demand restrike potential of all homes. The HEM also successfully performs load shifting and rescheduling. Hence, the proposed DR algorithm is more efficient and effective than the simple DR algorithm in mitigating the undesired impacts of the DRK.

Based on the PC with Intel core i7-3820 CPU @3.60 GHz, 12 GB RAM, and Windows 7 64-bit operating system, the algorithm computation time is in order of several 100 ms for the TRA to allocate $\mathbf{DL}_{\boldsymbol{H}}^{*}$ or reallocate $\mathbf{DL}_{\boldsymbol{H}}^{*}$ to HAs according to the request from DR AGG. This computation time is considered sufficiently fast to perform control at the transformer level and at the household level as appliances are typically controlled at minute intervals.

VI. CONCLUSION

This paper presents an approach for SDTM using autonomous distributed-decision making entities. It shows how the physical-layer entities (i.e., TRs, homes, appliances) are integrated with the cyber-layer entities (i.e., TRA, HA, and the stand-alone HEM). In addition, this paper proposes the DR algorithm embedded in the cyber layer. The case study shows that the proposed algorithm can effectively perform DR implementation and achieve TRAs and HAs goals. At the TR level, the proposed approach ensures that an instantaneous power demand at the TR does not exceed a given DL while simultaneously minimizing impacts of demand restrike. At the home level, the proposed approach ensures that all critical loads are served and homeowner's comfort level is maintained during a DR event. At the appliance level, additional operating times of appliances due to load shifting and rescheduling during a DR event are minimized. Simulation results show that the proposed DR algorithm outperforms the simple DR algorithm as the resulting demand restrike potential is reduced by 56%.

In future work, the proposed approach can be improved by considering such factors as implementation costs, transformer's loss of life, or economic aspect of electricity market. Some of the load forecasting algorithms, such as nonlinear regression or neural network techniques, can be used to forecast load profiles of a TR based day type (weekday/weekend), weather, season, etc. Future work can also include scaling-up the proposed MAS to handle DR for a distribution network with multiple TRs that have a number of homes and controllable appliances. In addition, the proposed MAS can be deployed in a small single-board computer with limited computation capability. Such work is ongoing at the Virginia Tech Advanced Research Institute and will be reported in the future.

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