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Integrating Direct and Indirect Load Control for Congestion Management in LV Networks

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Abstract—With the energy transition, capacity challenges are expected to occur more frequently in low-voltage (LV) distribution networks. In the literature, several direct and indirect load control methods have been suggested as solutions to alleviate network congestion. Direct methods involve the network operator directly controlling appliances at the households, while indirect methods aim to motivate end-users to shift their consumption through price changes. In this research, the direct and indirect methods are combined into an integrated approach, making use of the advantages of both methods. An agent-based architecture is adopted so that distributed and computational intelligence can be combined to ensure a smooth coordination among the actors. A sensitivity-based curtailment scheme is used to incorporate the unbalanced loading condition of the LV networks. The efficiency of the proposed integrated approach is investigated through simulations in the unbalanced IEEE European LV test feeder. Simulation results reveal up to 94% reduction in congestion by the integrated approach, while maintaining the required levels of supply in the network.

Index Terms—Congestion management, Demand response, Graceful degradation, Integrated approach

I. INTRODUCTION

Congestion or thermal overloading of network assets (e.g. lines, cables, transformers) is caused by power flows exceeding its rated power. Frequent overloading affects the lifetime of network assets and necessitates a replacement of these assets involving a substantial cost. However, thermal overloading can be mitigated by incorporating the flexibility in the loads of the end-users through different direct and indirect control methods [1]. The direct control methods involve the DSO directly controlling appliances of an individual end-user [2], [3], [4]. A graceful degradation method is proposed in [5], that enables the DSO to limit the power flows at connection points based on predefined contractual agreements. However, concerns exist regarding the privacy and fairness of the use of direct control, since curtailment decisions need to distinguish among the connected end-users. Since the residential end-users are mostly equipped with a single phase connection, active power curtailment may lead to a higher voltage unbalance factor towards the end of the feeder [6]. Moreover, from the perspective of a liberalized energy market, flexibility ideally needs to be procured through the market [11].

Contrary to the direct control, the indirect control motivates end-users with market-controlled Demand Response (DR) mechanisms through different price-based schemes including day-ahead dynamic tariffs, time-of-use (ToU) pricing, critical peak pricing (CPP), real-time pricing (RTP) etc [7], [8]. Different types of locational marginal price (LMP) or distribution congestion price (DCP) have been investigated in order to address the problem of thermal constraint violations in distribution networks [9], [10]. However, market-based methods essentially depend on the willingness and availability of demand flexibility and are therefore may not be able to resolve the congestions completely. To this end, a direct control approach can complement market-based schemes to enhance the overall flexibility in the network significantly [5]. Application of both direct and indirect control for real-time congestion management has been investigated in [8]. The dynamic thermal model of the transformer has been used quantify the cost incurred due to overloading. The PowerMatcher scheme is used to coordinate the entities and procure flexibility to alleviate the overloading cost. A uniform curtailment scheme has been adopted to limit connection capacity when congestion cannot be resolved through the market. A local market framework incorporating day-ahead and real-time operations is proposed in [11] that aims to minimize the cost for network support through voluntary and compulsory participation of the prosumers. A spatially distributed hierarchical control architecture is discussed in [12], that incorporates the network reconfiguration possibilities along with market-based flexibility. An incentive-based DR program is used in [13] in order to determine optimal dispatch of a grid-connected microgrid providing flexibility services to the network.

In this research, an integrated solution for day-ahead congestion management is defined by incorporating an advanced market-based mechanism with a graceful degradation method based on flexibility contracts. Specifically, a sensitivity-based approach is adopted to consider the impact of curtailment on the voltage unbalance factor at the end of the feeder. The integrated approach combines the advantages of the direct and indirect control methods and ensures a more reliable operation of the network. The approach makes use of the distributed intelligence within an agent-based environment. A detailed case study is performed on a modified IEEE European LV test network in order to investigate the efficiency of the proposed approach. The main contributions of the paper are as follows:

- an integrated approach of congestion management com-

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bining market-based demand response and direct load control methods is defined;
- a sensitivity-based scheme is proposed to incorporate the effects of unbalanced loading in the LV networks;
- a smooth coordination is enabled through agent-based distributed architecture;
- flexible capacity arrangements are applied in order to identify suitable curtailment locations.

The paper is organized as follows: Section II presents an overview of the integrated approach along with the coordination of the related entities followed by, Section III which describes the mathematical formulation of the proposed approach. Section IV provides the description of the test scenario and the adopted assumptions. The simulation results are presented and analyzed in Section V. Finally, the conclusions on the application of the integrated approach are drawn in Section VI.

II. INTEGRATED SCHEDULING APPROACH

A. Overview

With the growing implementation of advanced ICT infrastructure and the increasing share of distributed energy resources (DERs) and flexible appliances in residential distribution networks, market-controlled operation involving small-scale prosumers has been drawing a significant research interest in recent years. Attempts have been made to incorporate the flexibility of residential loads through transactive energy frameworks with varied scopes and aims [14]. Local flexibility oriented market-based mechanisms have been shown to be one of the most promising alternatives for ancillary services like overall system balancing [15], [16], [17] and network congestion management [18], [19]. However, in a market-controlled distribution network with a dominant share of price-responsive loads, the load of individual households tends to coincide with each other. While the coincidence among the households is generally 0.2 [20], with price-responsive loads this can easily increase up to 0.6. This results in a higher peak load of the network, and consequently in overloading of network assets [21].

In this work, we aim to incorporate an active power curtailment based graceful degradation mechanism with a market-based control scheme. This integrated approach allows the network operator to address congestions, even when flexibility cannot be procured from the market. The market control method is designed by incorporating a dynamic day-ahead price and is coordinated by a commercial market party such as - an aggregator. Aggregators are responsible for managing the local flexibility in their cluster of contracted end-users and supplying the DSO with a schedule of the loading for the following day. In case congestion is expected, the dynamic price levels are adjusted by the aggregator to shift flexible loads in order to reduce the peak and in turn, alleviate the congestion. In case the aggregators are not able to influence the end-users with a suitable price signal, the DSO invokes the graceful degradation mechanism to limit network access of certain users in terms of their contracted connection capacity.

As highlighted in [22], two distinct types of connection capacities can be identified, namely:
- Firm-capacity: The non-curtailable part of the total connection capacity. The firm-capacity cannot be curtailed by the DSO, and needs to be constantly maintained;
- Non-firm capacity: The curtailable share of the connection capacity. The non-firm capacity is subject to curtailment upon availability based on contractual agreements involving a maximum allowable duration and frequency of curtailment per point of connection (POC). Through the inclusion of the maximum duration and frequency of curtailment some level of fairness is introduced and users can voluntarily opt for being curtailed less or more often.

The application of the integrated approach hinges on a robust and reliable communication among different actors in the energy value chain. An agent-based distributed system architecture is adopted in this research that provides for an efficient platform for smooth and reliable coordination among the related actors. An overview of the distributed architecture and associated interactions are presented in Section II-B.

B. Distributed coordination

1) System architecture: A hierarchical agent-based architecture is adopted in this research, comprising of device agents, household agents, an aggregator agent and a network agent. All of the loads and DG units connected in the LV network are represented by device agents (DAs). The DAs are responsible for the optimization of related appliances based on the price signals and internal constraints. DAs are coordinated by a household agent (HA) that interacts with the external market and network agents through an aggregator. The aggregator coordinates the contracted prosumers through dynamic prices and supports the network operator with the flexibility of the end-users in its portfolio. In addition, the transformer agent (TA) is implemented as a network agent to monitor and control the MV/LV transformer. The agent-based environment allows the system to be highly scalable, since more end-users and more appliances can be easily integrated in terms of new agents. At the same time, the environment can be expanded to wider network segments by including more MV/LV transformers in terms of additional TAs. A more detailed description of the system architecture can be found in [21].

2) Interaction: The interaction among the agents is graphically presented by means of a UML sequence diagram in Fig. 1. The process of the integrated approach starts with the DAs preparing the projected consumption based on the day-ahead price supplied by the aggregator. The HA combines the device profiles into the day-ahead household profile and sends it to the aggregator. The day-ahead load profile of house, \( i \) comprises of the flexible load, \( P^{f}_{i,flex} \), and uncontrollable base load, \( P^{i}_{base} \). Since the flexible load comprises of buffered and time shifting appliances, \( P^{f}_{i,flex} \) is given by,

\[
P^{f}_{i,flex} = \sum_{a=1, a \notin A^{flex}} P^{i}_{a} + \sum_{a=1, a \in A^{flex}} P^{i}_{a} \quad \forall t \in T, i \in H \quad (1)
\]
where, \( P_{t,a}^i \) indicates the consumed power at time, \( t \) by the \( a \)-th appliance, while \( H, T, A_{bf}^i \) and \( A_{ts}^i \) denote the sets of all households, time steps, buffered and time shifting appliances respectively.

The load profiles are subsequently forwarded to the TA for a network congestion analysis. In case congestion is expected, the TA requests the aggregator for flexibility during the time when the congestion occurs. Following the request, the aggregator runs an iterative process to try and procure the desired flexibility from the HAs by adjusting the dynamic price. An adjusted price is communicated to the HAs, who in turn send back an adjusted load profile. In case the price adjustment fails to reduce the network load to the associated limits, the TA overrules the market and runs the process of graceful degradation to determine curtailment plan for the next day. The curtailment plan includes the information of the time, location and amount of active power curtailment in the network. Based on the developed plan, the TA sends the curtailment signal to the HAs directly. Finally, related HAs reoptimize their appliances based on the imposed curtailment constraints.

III. MODELING

The modeling of the integrated approach of day-ahead congestion management consists of two parts, the market-based demand response modeling and the modeling of the graceful degradation. Both of the options require the use of household load data on the appliance level, as the level of flexibility differs depending on the type of appliance. In order to generate the load curves of the appliances in a household, a bottom-up Markov Chain Monte Carlo approach to the household load modeling is applied [23]. Based on this approach the preferential household load curve can be determined comprising of different devices. Subsequently the household load is subjected to the dynamic price from the aggregator. How the appliances in the household react to a dynamic price is discussed in the next section.

A. Market-based demand response

As discussed in Section II, the market-based control involves interactions between the aggregator and the household, where the households respond to the dynamic price sent by the aggregator by adjusting the initial load profile. The price is later altered, if a congestion is expected. First, the response of the devices to the price signals is elaborated, followed by an explanation of the adjustment of price levels.

1) Appliance response modeling: Each household has multiple types of appliances which will react differently to a change in price. Four different types of appliances can be distinguished: non-controllable appliances, time shifting appliances, buffer appliances and curtailable appliances [24]. The main flexible appliances (EV, PV, heat pump, washing machine, fridge, and dishwasher) in the household are characterized as one of these types of loads. The other appliances are considered to be non-controllable and will not be affected by the dynamic price. The household tries to limit the cost of energy by changing the scheduled operation based on the dynamic price. This can be expressed by the following optimization problem:

\[
\min_{a=1}^{\mid A \mid} \sum_{t=1}^{N_T} p_t \times P_{t,a} \quad (2)
\]

where \( A \) is the set of all appliances within a single household, \( N_T \) the number of time steps in a day and \( p_t \) the price at time \( t \) and \( P_{t,a} \) the power of appliance \( a \) at time \( t \). The appliance scheduling which needs to be optimized covers two groups of appliances: time shifting and buffered appliances [25]. For the different groups of appliances it can be assumed that there energy use is independent of one another, allowing eq. (3) to be rewritten as:

\[
\sum_{a=1}^{\mid A \mid} \min_{t=1}^{N_T} p_t \times P_{t,a} \quad (3)
\]

The optimization of the appliances can now be defined for the two main groups of appliances. The buffered appliances follow the following optimization:

\[
\min_{t=1}^{N_T} p_t \times P_{t,a} \quad \forall a \in A_{bf}^i \quad (4)
\]

subject to,

\[
\sum_{t=k}^{t=k} P_{t,a} = \sum_{t=k}^{t=k} P_{t,a}^0 \quad \forall a \in A_{bf}^i, k \in T \quad (5)
\]

\[
\min_{t} P_{t,a}^0 < P_{t,a} < \max_{t} P_{t,a}^0 \quad \forall a \in A_{bf}^i, t \in T \quad (6)
\]

where \( x_a \) is the maximum buffer time for appliance \( a \), \( P_{t,a}^0 \) the original load of appliance \( a \) at time \( t \), \( T \) the set of the time steps in a day and \( A_{bf}^i \) the set of buffer appliances. With this optimization, the energy usage of the appliance is kept constant. Through the constraint in eq. (5), only the energy use within a predetermined amount of time \( x_a \) can be altered from the original energy usage \( P_{t,a} \). The value of \( x_a \) should be determined for the different appliances. For the freezer and the refrigerator the value of \( x_a \) is estimated based on [26], for the heat pump the value of \( x_a \) is taken from [27] and for the EV the value of \( x_a \) is determined by the leaving time of the EV. For the time shifting appliances the optimization can be written as:

\[
\min_{t=1}^{N_T} p_t \times P_{t+a} \quad \forall a \in A_{ts}^i \quad (7)
\]

subject to,

\[
\sum_{t=1}^{N_T} P_{t,a} = \sum_{t=1}^{N_T} P_{t+a,a} \quad \forall a \in A_{ts}^i \quad (8)
\]

\[
\tau_{min,a} < \tau < \tau_{max,a} \quad \forall a \in A_{ts}^i \quad (9)
\]

where \( \tau \) is the time shift of the appliance, \( \tau_{min,a} \) and \( \tau_{max,a} \) the limits of the maximum allowable time shift and \( A_{ts}^i \) the set of all time shifting appliances. For the optimization of the time shifting appliances the time shift \( \tau \) is the decision variable rather than the power at each time instant. The limits
Aggregator
Device agent
Household
agent
Transformer
agent
Day-ahead
dynamic price
Day-ahead
dynamic price
Day-ahead
profile
Day-ahead
profiles
Consumption
profile
Flexibility
request
Profile
Price
Available
flexibility
Price
Profile
Curtailment
request
Curtailment
request
Adjusted
profile
Adjusted
schedule
Normal
operation
Market-based
peak reduction
Graceful
degradation
Fig. 1. Interaction among the involved agents.

of $\tau$ for the dishwasher as well as the washing machine are determined from a pilot project [28]. The only curtailable appliance considered from a market perspective is the PV. For the curtailment the optimization problem for the PV can simply be stated as:

$$\min_{t=1}^{N_T} p_t \times P_{t,PV}$$

subject to,

$$0 < P_{t,PV} \leq P_{0,t,PV} \quad \forall t \in T \quad (11)$$

where, $P_{t,PV}$ denotes the generated active power from the solar PV system at time, $t$.

2) Market-based price adjustment: As shown in Fig. 1, the TA requests flexibility from the aggregator, when a congestion is anticipated. In such a case, the aggregator tries to alleviate the peak loads through iterative changes in the price. In each iteration, the households react by reoptimizing the appliances based on eq. (4) -(11). The iterative process aims to find a suitable adjusted price that reduces the peak loads to the agreed upon level with the DSO. This adjusted price signal $p_{t,new}$ is based on the following equation:

$$p_{t,new} = \frac{1}{5} \sum_{t'=-2}^{t+2} \left\{ p_t + p_{adj} \right\} \left\{ \begin{array}{ll} p_t, & \text{if } S_{t_f} \geq S_{rated} \\ p_{adj}, & \text{otherwise} \end{array} \right\}$$

where $p_{adj}$ is the incremental price adjustment, $S_t$ is the system apparent power at time $t$ and $S_{rated}$ is the rated power. After the updating of the price the system apparent power $S_t$ is recalculated with the household load profiles adjusted to the new price $p_{t,new}$. If the adjustment in the peak load is not sufficient, the aggregator adjusts the price again according to eq. (12) until the required peak reduction is reached or the required price difference becomes uneconomical from the aggregator's point of view.

The DSO only pays a limited amount to the aggregator to reduce the peak load as it has the backup option of obtaining peak reduction through graceful degradation. The change in peak load generates a sub-optimal load profile from the market perspective. The aggregator has to bear the cost for this suboptimal load profile while it gets compensation from the DSO. If the DSO compensation is not sufficient, the aggregator reverts to its original market price as the aggregator needs to be able to generate benefits for the consumer in order to have a viable business model. Not reverting back to the original price increases the net energy cost (energy cost plus the DSO incentive) above the original level.

B. Graceful degradation

The process of graceful degradation is coordinated by the TA and is activated only when the aggregator fails to reduce the peak loads through price adjustments. In order to relieve network congestion, graceful degradation limits the consumption level at certain households. The day-ahead curtailment plan is developed based on a target loading level, the voltage unbalance, the available non-firm capacity and the household preferences represented by the maximum frequency and duration of curtailment. Upon receiving a curtailment request from the TA, the households optimize their appliances to adhere to the prescribed loading level supplied by the TA.

1) Sensitivity of the voltage unbalance factor: Since residential customers are connected in single phase, active power curtailment at POCs may lead to voltage unbalance in the network. The degree of unbalance is measured by the voltage unbalance factor, $VUF$ and becomes more pronounced along the length of a LV feeder from the substation. As shown in eq. (13), the voltage unbalance factor, $VUF$ is calculated from the symmetrical components of the voltage at the POC [7], [29].

$$\%VUF = \frac{V^-}{V^+} \times 100$$

(13)
where, $V^-$ and $V^+$ are the negative sequence and positive sequence voltage at the POC respectively. According to the EN50160 standard, the 10-minute average RMS value of $VUF$ must be limited to 2% for the 95% of the time in a week [13].

In this work, the sensitivity of $VUF$ at the end of a feeder to the changes in power consumption at the POCs is determined to limit voltage unbalance resulting from active power curtailment. The sensitivity of $i$-th POC, $\left(\delta(VUF)/\delta P^i\right)$ is estimated by the changes in $VUF$ at the end of the feeder due to a change in power consumption at the same POC.

2) Development of curtailment plan: The curtailment plan corresponds to the location, time step and requested amount of active power curtailment at each POC. From the perspective of TA, the decision making algorithm can be formulated as an optimization problem, that minimizes the required curtailment, as shown in eq. (14).

$$\min_C \sum_{i=1}^{N_T} \sum_{t=1}^{N_b} C^i_t$$ (14)

subject to,

$$C^i_t \leq u^i_t P_{non\text{-}firm} \quad \forall i \in H, t \in T$$ (15)

$$\sum_{i=1}^{N_b} C^i_t \leq C^{max}_t \quad \forall t \in T$$ (16)

$$z^i_t \leq u^i_t \quad \forall i \in H$$ (17)

$$z^i_{t+1} \leq u^i_{t+1} \quad \forall i \in H$$ (18)

$$z^i_t \geq u^i_t + u^i_{t+1} - 1 \quad \forall i \in H$$ (19)

$$\sum_{t=1}^{N_T} u^i_t - z^i_t \leq F^{\max}_i \quad \forall i \in H$$ (20)

$$\sum_{t=3}^{N_T} u^i_t + u^i_{t-1} + u^i_{t-2} \leq \Psi^i_{max} \quad \forall i \in H$$ (21)

$$(VUF)_t + \sum_{i=1}^{N_T} C^i_t \left(\frac{\delta(VUF)}{\delta P^i}\right) \leq 0.02 \quad \forall t \in T$$ (22)

where, $C^i_t$ is the decision variables that denotes the amount of curtailment at $i$-th household; $u^i_t$ is binary in nature and assumes a value of 1 when $i$-th household is selected for curtailment; $z^i_t$ is a binary dummy variable that helps restricting the frequency of curtailment; $N_b$ indicates the total number of household in the network and is given by the number of elements in the set of all households, $H$.

Constraints in eq. (15) and (16) limit the curtailed power in each household within the contractual non-firm capacity, $P^i_{non\text{-}firm}$ and curtable power, $P^i_{t\text{-}curt}$ at time, $t$ respectively. The curtable power refers to the instantaneous available non-firm capacity. Constraints described by eq. (18) - (21) ensure that the maximum allowable frequency ($F^{\max}_i$) is not violated; similarly, constraint (22) limits the duration of curtailment per household within the predefined limit ($\Psi^i_{max}$). Constraint (17) is imposed to limit the total curtailment within the desired margin of $C^{min}_t$ and $C^{max}_t$. The margins indicate the minimum and maximum levels of curtailment and are calculated based on the thermal rating and the target loading level respectively.

$$C^{min}_t = \begin{cases} S_t - S_{rated} & \forall S_t > S_{rated} \\ 0 & \text{otherwise} \end{cases}$$ (24)

$$C^{max}_t = \begin{cases} S_t - S_{target} & \forall S_t > S_{rated} \\ 0 & \text{otherwise} \end{cases}$$ (25)

$(VUF)_t$ denotes the voltage unbalance factor at the end of the feeder at time $t$. Constraint (23) ensures that the aggregated curtailed power at the POCs do not result in a violation of the maximum allowable unbalance factor of 2%.

The optimization problem, as defined by eq. (14) - (23) contains both integer and continuous variables and is therefore solved using a mixed-integer programming method.

3) Household response: Since the curtailment request indicates the time and amount of curtailment for each house, the HA first determines the devices that need to be switched off at the designated time steps. For each house, $i$, this can be mathematically formulated as the following optimization problem,

$$\min \left| C^i_t - \frac{n\left(A^{ts} \cup A^{bf}\right)}{} \right| v^i_{t,a} P^t_{a} \quad \forall t \in T_{curt}^b$$ (26)

where, $T_{curt}^b$ denotes the set of time steps in which curtailment is required and $n\left(A^{ts} \cup A^{bf}\right)$ represents total number of available time shifting and buffer appliances in house, $i$. The decision variable, $v^i_{t,a}$ is a binary variable and equals to 1, when a particular appliance needs to be switched off.

Once the HA determines the switching actions of the devices, by applying the appliance level optimization as defined by eq. (2) - (11), the optimization is performed once again with an additional constraint for each type of the devices, as shown in eq. (27) and (28).

$$\min_T P^{0}_{t,a} v^i_{t,a} < P_{t,a} < \max_T P^{0}_{t,a} v^i_{t,a} \quad \forall a \in A^{bf}, t \in T$$ (27)

$$\sum_{t=1}^{N_T} P_{t,a} = \sum_{t=1}^{N_T} v^i_{t,a} \times P_{t+a} \quad \forall a \in A^{ts}$$ (28)

The overall process of the integrated approach can be schematically presented by the flowchart shown in Fig. 2.

IV. SIMULATION SETUP

A. Load modeling

For the simulation of the congestion management approaches, the household load first needs to be determined. As the household load will be assessed differently for different types of devices, the flexible devices need to be modeled separately. The residential loads are therefore subdivided into seven categories: base load, EV, PV, heat pump, washing machine, dishwasher and refrigerator. The base load consists of all non-controllable devices (tv, microwave, etc.). The required EV charge is modeled based on the driving distance, arrival and departure time [30]. The charging rate is assumed
to range between the 3 and 8 kW. For the PV, the rated power varies between the 2 and 5.5 kW per household, facing in a southwestern to southeastern direction. The heat pumps have a rated power of 0.7 kW to 2 kW, with an additional 2 kW resistive heating element. The washing machine, dishwasher and refrigerator have a rated power in the range of 0.6-2 kW, 0.5-1.11 kW and 0.035-0.140 kW respectively. The original switching times of these appliances are modeled based on reported user behavior. A constant power factor of 0.95 has been used for the analyses.

For the active power curtailment when the graceful degradation is activated, the maximum duration and the frequency of curtailment per household are assumed randomly distributed between 1-1.5 hours and 1 or 2 times per day respectively.

The flexible loads, i.e. EV, heat pump, washing machine, dishwasher and freezer are considered to comprise of the non-firm capacity available at each POC.

B. Test network

A modified European LV test network is used for the case study. The test network consists of 55 households equipped with single phase connections. A 250 kVA, 11kV/0.416kV transformer is used to supply the LV network from the MV bus. The transformer comprises of a delta/grounded-wye connection. The resistance and reactance of the windings are 0.4% and 4% of the base values at the MV side respectively. An additional LV feeder with an aggregated peak load of 100 kW, is assumed at the MV/LV substation.
C. Simulation platform

The simulation is performed with a time step of 15 minutes. The agent-based simulation platform is developed and coordinated in MATLAB environment. The appliance response optimization problems in eq. (2)-(11) are solved using MATLAB Optimization Toolbox [34]. Based on the load profiles, the power flow calculation is performed using the EPRI distribution system simulator, OpenDSS [33]. The optimization problem associated with graceful degradation in eq. (19) - (23) is modeled using open-source MATLAB toolbox, YALMIP [34]. YALMIP supports rapid prototyping of optimization problems and uses an external optimization solver. In this research, the Gurobi Optimization solver is used for solving the mixed-integer problem discussed in Section III-B [35].

D. Determining the sensitivity of $VUF$

The sensitivity of $VUF$ at the end of the feeder to the changes in power consumption is estimated by 40 simulations for each household. In each round of simulation, the $VUF$ at the end of the feeder is recorded, upon varying the power consumption at each household between 100 W and 4 kW with an increment of 100 W in each step. While varying the load of the selected house, the power consumption of the remaining houses is kept fixed. The process is repeated for 200 randomly selected samples from the generated load profiles.

Fig. 3 illustrates the effect of each household on the sensitivity by means of boxplots. The unbalance becomes more prominent along the feeder and reaches the maximum at its end. It is important to note that the effect of the load at a particular house varies within a very small range. Therefore, the 95th percentile value of the resulting sensitivity for each household is considered in the subsequent analyses.

V. Numerical results

Snapshots of the simulation results are presented for typical winter days in the Netherlands. First, the impact of dynamic pricing scheme on residential demand is discussed. Next, the impacts of the market-based DR and graceful degradation methods are explained separately, followed by the effects of applying the integrated approach. Subsequently, the monthly performance of the mechanisms is analyzed in terms of the overall efficiency of managing the congestion.

A. Effects of dynamic price

Fig. 4 illustrates the impact of the dynamic price on the aggregated network demand. The initial load profile represents the combined projected day-ahead profile of the households. Each HA adjusts its initial day-ahead profile considering the same dynamic price sent by the aggregator. The resulting network load is illustrated by the price-adjusted profile. As discussed in Section III, the HAs aim to minimize the energy cost by optimizing the daily energy usage of the devices. To do so, flexible devices are mostly scheduled during the times of lower price. Therefore, the peak loads in the adjusted network load profile are related to the valleys in the profile of the day-ahead price and vice versa. Thus, a lower domestic energy cost is realized by introducing the dynamic price at the expense of larger peaks from an LV-network perspective.

B. Market-based peak reduction

In order to resolve congestion, the DSO requests flexibility from the market. The aggregator, as the demand flexibility coordinator, determines if the requested flexibility can be delivered by adjusting the day-ahead price. Flexible loads of the end-users are influenced by varying the price levels, with an objective of reducing the peak load. Along with the change in price, the resulting adjusted load profiles are illustrated for two representative days in Fig. 5. In order to take advantage of the decreasing price at the late evening of the first day, EVs start charging almost simultaneously and results in overloading the transformer. Similar situation occurs in the evening of the second day, when the operation of the HPs coincide with the conventional residential peak loads.

Upon receiving the flexibility request from the TA, the aggregator increases the price levels during the times of peak demand. The off-peak price level is further reduced in order to maintain a constant daily average price. The HAs respond to the new price levels by re-optimizing the flexible loads. The effect of the increase in the price level during the peak is reflected in the load profile, as the maximum load is reduced to 0.99 p.u. from 1.03 p.u. Flexible loads are shifted in time and thereby keeping the total energy consumption of 4.84 MWh fixed in all of the cases.

C. Impact of graceful degradation

Fig. 6 presents the resulting load profile when only graceful degradation is applied. Simultaneous charging of EVs is seen to cause overloading at the midnight of the first day. The coincidence of the flexible loads with usual evening peak results in further congestion in the evening of both of the simulated days. Upon violation of the thermal rating, the TA selects the most suitable houses and limits their network access in terms of the connection capacity. The curtailment amount is determined considering the target loading, $S_{\text{target}}$, available flexibility of the households and the maximum duration and frequency of curtailment dictated by the flexible capacity contract.

For instance, the transformer is overloaded by 3.5% and 1.8% at 01:00 and 01:15 hours respectively on the first day. In order to resolve the congestion at these consecutive time steps based on available flexibility, the TA sends a curtailment request of 5.13 kW and of 4.49 kW to house no. 48. An additional request for 4.04 kW at 01:00 hours is sent to house no. 39, due to the higher required peak reduction. The HAs respond to the curtailment request by optimizing the available devices with the new constraints. The adjusted network load profile reveals fewer peaks as the loads are mostly shifted away from the peak times.
D. Overall performance of the integrated approach

The overall performance of the integrated approach is evaluated in terms of the congestion duration, maximum network load and total network supply for a simulation time window of one month. These performance indicators reveal the efficiency of the integrated approach for resolving the congestion while maintaining the reliability of supply. Table I summarizes the comparative performance among the market-control, graceful degradation and integrated approach. A significant reduction in the duration of the congestion is realized by the integrated approach with a slight drop in the total network supply. The reduced supply can be explained by the part of the curtailed load, which is shifted to the next day and hence is not considered within the simulation time frame.

The market-based demand response reduces the duration of congestion by almost 62% by shifting the load through price adjustments. The load shifting behavior results in a higher supplied energy compared to the graceful degradation and the integrated approach. However, the adjusted price may not always tackle the congestion, since it depends on the available flexibility. This is reflected in the magnitude of the peak load being the same for both the price-based and the market-controlled DR.

Contrary to the iterative process of the market-based control, graceful degradation sends the curtailment signals based on the
An integrated approach for day-ahead congestion management is formulated that combines the advantages of market-based indirect control and active power curtailment based direct control methodologies. The proposed approach avoids the shortcomings of the indirect and direct control methods, which makes it well-suited for congestion management in residential LV networks.

The integrated approach utilizes a hierarchical architecture, equipped with agent-based distributed intelligence. A detailed bottom-up Markov Chain Monte Carlo approach is used to model the price-responsive household appliances. Day-ahead household profiles are generated by scheduling the flexible appliances based on the day-ahead price in order to minimize the residential energy cost. If network congestion is expected, the aggregator tries to procure flexibility from the end-users by adjusting the day-ahead price. In case the price-adjustment cannot influence the end-users to shift their loads up to the desired margin, the DSO takes over and selects suitable locations for active power curtailment. To this end, the sensitivity of the voltage unbalance factor to the changes in residential demand is taken into account. This provides a better distribution of curtailment among the phases and prevents a higher voltage unbalance following active power curtailment.

The efficacy of the integrated approach is investigated through simulations for 55 households in the modified IEEE European LV test network. Simulation results show an association between the dynamic price and the occurrences of congestion, since flexible loads aim to reduce the energy cost as much as possible by shifting to times of low prices. The market-controlled DR is an efficient method to tackle the
most of the congestion which occurs, as the total monthly congestion duration can be lowered up to 62%. For safe operation of the network, the other 38% of the congestion has to be reduced, even if the price adjustment does not always succeed to procure sufficient flexibility. In such a case, a significant reduction (94%) in the congestion duration is achieved by complementing the market-controlled DR with a graceful degradation approach. Since the response of the appliances following the curtailment is explicitly modeled, the magnitude of the supplied energy remains of the same order. Based on the monthly simulation in an Intel Core i7 computer with 8GB of RAM, the integrated approach requires a simulation time of approximately 21 minutes compared to 14 minutes for the uncontrolled case.

By incorporating both direct and indirect control, the developed approach provides a reliable platform for network congestion management. Future research on this topic will be directed to the integration of voltage control methods in unbalanced residential networks. The aggregator functionality can be further upgraded by including suitable learning techniques to have better insights into the residential energy usage, unlocking more accurate price adjustments. The agent interaction model needs further modification to expand the approach to multiple aggregators. During the dispatch the predefined programs may not hold due to the uncertainties with load and local generation, and can lead to deviations which may require more or less peak reduction. The inclusion of this uncertainty within the evaluation of the proposed scheme should be further investigated to ensure a more robust and reliable operation.

REFERENCES


