Electric Power Systems Research 143 (2017) 462–473

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Agent-based unified approach for thermal and voltage constraint management in LV distribution network

A.N.M.M. Haque[a,*], P.H. Nguyen[a], T.H. Vo[a], F.W. Bliek[b]

[a] Department of Electrical Engineering, Eindhoven University of Technology, Den Dolech 2, 5612AZ Eindhoven, The Netherlands
[b] DNV GL Energy, 9704 CA Groningen, The Netherlands

ARTICLE INFO

Article history:
Received 20 March 2016
Received in revised form
30 September 2016
Accepted 7 November 2016
Available online 16 November 2016

Keywords:
Congestion management
Local voltage control
Direct load control
Unified approach
Droop control

ABSTRACT

Rapid proliferation of the distributed energy resources (DERs) poses operational challenges for the low-voltage (LV) distribution networks in terms of thermal overloading of the network assets along with voltage limit violations at the connection points. A number of market-based and direct control approaches have been widely developed to tackle these challenges with different objectives. While most of the techniques aim to solve the problems separately, an integrated and efficient method is missing to handle such correlated issues simultaneously. In this study, a unified approach combining local voltage control mechanism with a centralized congestion management scheme is proposed by utilizing an agent-based hierarchical architecture. The feasibility of the proposed approach is validated with a simulation analysis for a representative Dutch urban LV network considering up to 100% penetration of solar PV and electric heat pumps (HPs). The quantitative analysis reveals that, local voltage control strategies can essentially aid mitigating thermal overloading of the network assets. Thus, integrating a local voltage control method with a coordinated congestion management mechanism can enhance the system flexibility while maintaining the network constraints and the comfort levels of the consumers simultaneously.

1. Introduction

The electrical power distribution network has been conventionally developed in a 'fit-and-forget' approach due to the relatively longer life time of the network assets enabling a much longer planning horizon for the network operators [1]. With the widespread integration of distributed energy resources (DERs) including renewable energy sources (RES) and electrification of transport and heating sectors, the distribution network has been recently moving towards a more actively controlled system, so-called active distribution network (ADN) [2]. The intermittent and unpredictable nature of DERs pose various operational challenges like network congestions and voltage limit violations for the distribution network operators [2–4]. As reported in Ref. [5], network operators in Italy, Spain, Ireland and Germany having long feeder lengths and high RES penetration are facing frequent local voltage limit violations. On the other hand, densely clustered urban distribution networks are becoming more prone to network congestions in the upcoming years. In the Netherlands, a scenario-based analysis presented in Ref. [6] shows that, with future load growth and new generation technologies, 87% of the MV/LV transformers will be overloaded in 2040.

Network reinforcement has been considered as the conventional approach to tackle such network operational challenges. However, reinforcing the network components necessitates a huge investment although the peak loads will generally occur only for a few hours in a year [7–9]. An alternative approach is to utilize the existing infrastructure more efficiently by either a centralized or a decentralized control system. In Ref. [10], a centralized system using remotely controlled switches is investigated to minimize the amount of curtailed distributed generation (DG) to resolve overloads in a distribution network. A decentralized approach for real-time management of local voltage and thermal constraints is presented in Ref. [11] that avoids the need of extensive sensing and communication procedures. A robust solution of the load curtailment problem is presented in Ref. [12] that proposes a rolling horizon formulation of the optimization problem based on approximate dynamic programming (ADP) techniques. Advanced curtailment mechanisms based on 'hosting capacity' is presented in Ref. [13] to relieve congestions resulting from the RES-based generation technologies. A study performed in a typical Danish LV network is presented in Ref. [14] considering 100% penetration of HPs and EVs, which concludes that a simple merit-order based

* Corresponding author.
E-mail addresses: a.n.m.m.haque@tue.nl, abu.niyam@gmail.com (A.N.M.M. Haque).

http://dx.doi.org/10.1016/j.epsr.2016.11.007

direct control mechanism can efficiently tackle local congestions in the residential LV network. A mixed-integer programming based selection mechanism is presented in Ref. [15] for curtailment of active power consumption in radial LV network considering flexible capacity contracts.

Apart from congestion, voltage level violations have been a more frequent issue in the distribution networks with long feeder lengths and high penetration of DERs [16]. Due to the resistive feature of LV networks, active power curtailment becomes an effective solution to cope with voltage variations. Different approaches of active power curtailment have been widely studied to mitigate overvoltage in the LV networks [11,16–18]. A power factor management scheme is proposed in Ref. [16] to locally mitigate voltage rise to maximize the connected DG capacity. The method is extended to a two-stage mechanism prioritizing reactive power control at lower opportunity cost while using generation curtailment as the last alternative [11]. A droop-based active power curtailment methodology is proposed in Ref. [18] for overvoltage prevention in the residential LV networks. A sensitivity-based droop characteristic is devised to allow a uniform curtailment for connected inverters in a radial distribution feeder. A multi-agent systems (MAS) based hierarchical approach of active power curtailment is presented in Ref. [17] that combines a droop-based local control with a centralized overlaying control in order to curtail the PV injection fairly among the consumers.

While most of the techniques aim to solve the network problems separately, these issues are subject to change along with the different time horizons, i.e. peak and off-peak times, weekdays and weekends, or with seasonal variations. Furthermore, they are correlated and might occur in different network levels, i.e. voltage violations at the local level of the point of common coupling while network congestions are likely at the area level of the distribution transformer or main outgoing feeders. The aim of this paper is to solve these correlated issues with the following main contributions:

- A unified approach to deal with both network congestions and voltage limit violations in various time horizons, and
- An agent-based hierarchical architecture to exploit flexibility resources from different DERs in the LV network considering up to 100% penetration of solar PV and HPs.

The remainder of the paper is organized as follows. First, the problems of congestions and voltage limit violations in a radial LV network are analyzed. Next, the proposed unified approach is discussed along with the decentralized system architecture followed by the description of the related case study. Finally, simulation results are presented and conclusions are drawn with recommendations for possible future works.

2. Problem analysis

2.1. Voltage variations

Owing to the very high number of connected end-users and diversity of loads, voltage variations in the LV networks are higher than the same in the MV and HV networks. In a radial LV network, voltage variation depends not only on the local power consumption but also on locally injected power and the impedance of the network [17]. Voltage at the receiving end of a cable section, V_R can be expressed as,

$$V_R = V_S - I_R(R + jX) \tag{1}$$

Table 1
R/X values for typical LV distribution cables.

Cable type	R (Ω/km)	X (Ω/km)	R/X
150 mm² Al	0.206	0.079	2.61
95 mm² Al	0.320	0.082	3.90
50 mm² Al	0.641	0.085	7.54
16 mm² Al	1.910	0.096	19.90
35 mm² Cu	0.532	0.074	7.19
50 mm² Cu	0.387	0.072	5.38
10 mm² Cu	1.837	0.088	20.88
6 mm² Cu	3.061	0.100	30.61

where $R + jX$ is the impedance of the distribution cable, V_S is the voltage at the sending end, and I_R denotes the current through the cable section.

If the connection point at the receiving end constitutes local active and reactive power generation P_G and Q_G, with local active and reactive power consumptions P_L and Q_L respectively, Eq. (1) can be rewritten as,

$$V_R = V_S - \left\{ \frac{(RP_R + XQ_R) - j(RQ_R - XP_R)}{V_R} \right\} \tag{2}$$

where $P_R = |P_L| - |P_G|$ and $Q_R = |Q_L| - |Q_G|$.

As shown in Table 1, typical LV underground power cables are predominantly resistive in nature due to a high R/X ratio. Consequently, the active power has a bigger impact on the voltage variations along the feeder [19–22]. Thus Eq. (2) can be simplified as:

$$V_R \approx V_S - \left\{ \frac{(RP_R)}{V_R} \right\} \tag{3}$$

As a result, the relation between the sending and receiving end voltages can be represented as shown in Eq. (4).

$$\begin{aligned} &V_R > V_S \text{ when, } P_G > P_L \\ &V_R < V_S \text{ when, } P_G < P_L \end{aligned} \tag{4}$$

In order to compensate for the voltage drop and to avoid subsequent undervoltage at the end of the feeder, the secondary side voltage of a MV/LV transformer is usually set at 1.01–1.05 p.u. [23]. However, when the local generation at the connection points exceed local loads, voltage level along the feeder rises and the connection point at the end of the feeder experiences overvoltage. On the other hand, another feeder with a higher amount of loads than local generation experiences voltage drop along the feeder.

2.2. Network congestions

Congestions or thermal overloading are likely to occur for cables as well as the transformers in the network. However, for the sake of simplicity, the focus of this work is limited to addressing the congestions in the MV/LV transformer only. Loading of a MV/LV transformer can be calculated from the current flowing in the outgoing feeders. V_s and I_s being the voltage at the LV bus and total current respectively, instantaneous load of the transformer at time t, S_{ins}^t is given by:

$$S_{ins}^t = V_s I_s \tag{5}$$

Congestions occur in a MV/LV transformer when the loading of the transformer, S_{ins}^t exceeds the thermal rating, S_{max} caused either by increased residential loads or reverse power flows from the domestic DG units. Consequently, congestions can occur simultaneously along with the local voltage limit violations in the network. A coordinated mechanism is therefore necessary in order to limit residential consumptions or curtail active power production at the connection points for resolving the congestion. For the sake of simplicity, both of the cases will be termed as active power curtailment in the remainder of the paper. To relieve the congestion, total required curtailment, $P_{curtail}$ can thus be calculated as:

$$P_{curtail} \geq |S_{ins}^{t}| - |S_{max}| \tag{6}$$

$$P_{curtail} = \sum_{i=1}^{N} P_{curtail,i} \tag{7}$$

where $P_{curtail,i}$ denotes the amount of curtailed active power at each of the N connection points downstream of the transformer.

2.3. Correlation of network issues

As shown in Eq. (5), congestion in the transformer necessitates a higher flow of current in the network which causes an increased voltage drop along the cables. Consequently, voltage levels at the end of the feeder gets lower and undervoltage problems become prominent. HV/MV transformers are usually equipped with On Load Tap Changers (OLTC) to keep the voltage levels within a desired range of values. This enables to keep the voltage levels in the MV feeders uncorrelated and regulate downstream MV and LV networks. Unlike their HV/MV counterparts, MV/LV transformers normally have a fixed tap setting which can only be altered through an off-line maintenance. Hence, voltage levels in the LV networks are subject to frequent fluctuations following the change in the upstream MV networks [23].

With the increasing share of the RES-based local generation, increasing the voltage set point at the secondary side of the MV/LV transformer does not represent an optimal solution to tackle these voltage problems in the LV network. Different types of mechanisms are being used to tackle such problems for example-by reinforcing the network assets, shifting loads or by curtailing active power injection [7,24–26]. However, the operational challenges of such voltage variations and congestions are subject to large variation, depending on the daily and seasonal differences in load and generation patterns. Finding a suitable solution is therefore difficult due to the inherent unpredictability of the network operations. A unified approach is therefore significant to address the needs in the same network in different times of the year.

3. Proposed unified approach

The proposed unified approach aims to manage thermal overloading of the MV/LV transformer along with the voltage limit violations at the connection points. A decentralized local control method is adopted to continuously monitor and mitigate voltage level violations at the connection points.

LV distribution networks are typically allowed to operate within a certain range of nominal voltage, V_{min} and V_{max}. Therefore, the voltage level at connection point, i is bound by the following constraint [27],

$$V_{\min} \leq V_i \leq V_{\max} \quad \forall i \in N \tag{8}$$

where N denotes the set of connection points in the network. In this work, the upper and lower limits are considered to be 1.1 p.u. and 0.9 p.u. respectively. The local control mechanism optimizes domestic appliances and local generation units in order to maintain the voltage levels within the acceptable margin.

The unified approach is formulated by complementing the local control with a centralized congestion management mechanism (CM) as shown in Fig. 1. Unlike the local control, the centralized control is executed in discrete time steps. The process is coordinated by the distribution system operator (DSO) as the conditions at time $t = t_0$ dictates the actions to be implemented at time $t = t_0 + \Delta t$,

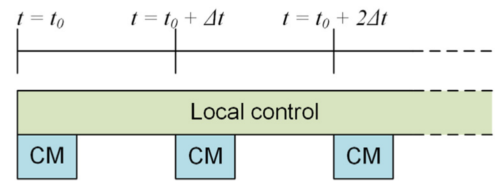

Fig. 1. Formulation of the unified approach by local voltage control and congestion management.

where Δt represents the time interval between two consecutive steps.

Upon violation of the thermal constraints of the transformer, a curtailment plan is prepared to identify the locations and amount of active power curtailment. Preferences of the individual connection points are considered in terms of comfort levels and fairness of generation curtailment. Thus, the overall objective of the approach can be formulated as minimization of the interruption while maintaining the consumers' preferences and comfort.

$$\min P_{curtail} \tag{9}$$

subject to,

$$P_{curtail} \geq |S_{ins}^{t}| - |S_{max}| \tag{10}$$

3.1. Local voltage control

In this research, we aim to cope with both under- and overvoltage problems by introducing the following mechanisms:

3.1.1. Overvoltage mitigation

Two distinct control schemes are discussed that aim to curtail active power injection from the PV inverters when voltage levels exceed certain threshold values. The mechanisms are as follows:

a. P-V droop control

Different types of droop control methods namely *P-V*, *Q-V*, *P-f* have been discussed and implemented as effective tools to maintain the security constraints of the network [16,17,28–31]. The well-established *P-V* droop control mechanism has been integrated in this work, where output active power of the PV inverter, P_{net} is set at the maximum power point, P_{MPP} during normal operations and is reduced following a linear function if the voltage levels at the connection point, V_m exceeds the threshold level of V_{uth}. As shown in Eq. (11), the inverter is switched off when the voltage levels exceed the upper limit of the acceptable range, V_{ub}.

$$P_{net} = \begin{cases} P_{MPP} & \forall V_{nom} < V_m \leq V_{uth} \\ P_{MPP} - P_{MPP}\dfrac{(V_m - V_{uth})}{(V_{ub} - V_{uth})} & \forall V_{uth} < V_m < V_{ub} \\ 0 & \forall V_m \geq V_{ub} \end{cases} \tag{11}$$

where V_{nom} denotes the nominal voltage levels at the individual connection points.

b. Sensitivity-based control

The sensitivity-based control aims to trim active power injection from the PV inverters based on a voltage/active power ($\delta V/\delta P$) sensitivity calculation [16,32]. The method takes in account the instantaneous voltage levels at the connection point, V_m and in case of the violation of threshold (V_{uth}), calculates the required amount of curtailment, ΔP as expressed by Eq. (12). The resulting power output, P_{net} can thus be calculated as shown in Eq. (13).

$$\Delta P = \frac{V_m - V_{uth}}{\delta V/\delta P} \tag{12}$$

$$P_{net} = \begin{cases} P_{MPP} & \forall V_{nom} < V_m \le V_{uth} \\ P_{MPP} - \Delta P & \forall V_{uth} < V_m < V_{ub} \\ 0 & \forall V_m \ge V_{ub} \end{cases} \quad (13)$$

The voltage/active power sensitivity depends on the network topology. In a radial LV distribution network, the sensitivity remains mostly of the same order and can be obtained from the Jacobian matrix through an off-line power flow calculation [17,18]. The value of the sensitivity can be set by the DSO at the local voltage control mechanism of the inverter and may be revised in case a modification in network topology is expected.

3.1.2. Undervoltage mitigation

Contrary to the overvoltage problem, undervoltage instants occur when the connection points in the network represent higher load consumptions as with the case of large-scale penetration of HPs for meeting the heating demand during the winter. The heat pumps are comprised of a pump that performs external work to transfer heat from a cold reservoir (air, water, ground etc.) to a warmer reservoir (house, buildings) and a resistive heating element. To prevent the undervoltage problems in the network, the power consumption of the heat pumps are controlled maintaining the thermal comfort of the inhabitants. Two different types of undervoltage control schemes are explained as follows:

a. Linear droop control

Linear droop control aims to curtail the active power consumption of the resistive heating element of the heat pump following a linear slope as illustrated in Fig. 2(a). P'_{HP} being the demanded power by the heat pump controller, upon violation of the lower threshold of the voltage limit, V_{lth} the active power consumption of the heating element, $P_{booster}$ is reduced following a linear function as shown in Eq. (14). The device is switched off in case only the pump is active in a particular time instant and voltage threshold is violated.

$$P_{HP} = \begin{cases} P'_{HP} & \forall V_{nom} > V_m \ge V_{lth} \\ P_{booster} - P_{booster}\dfrac{(V_m - V_{lth})}{(V_{lb} - V_{lth})} & \forall V_{lth} > V_m > V_{lb} \text{ and } P'_{HP} = P_{pump} + P_{booster} \\ 0 & \forall V_{lth} > V_m > V_{lb} \text{ and } P'_{HP} = P_{pump} \\ 0 & \forall V_m \le V_{lb} \end{cases} \quad (14)$$

where V_{lb} denotes the lower margin of the acceptable range of the voltage at the connection points.

b. Step control

As shown in Fig. 2(b), the step control switches off the resistive heating part when the measured voltage V_m drops below the lower threshold value of V_{lth}. Similar to linear droop case, as expressed in eq. (15) the device is switched off in case only the pump is active when the threshold is crossed.

$$P_{HP} = \begin{cases} P'_{HP} & \forall V_{nom} > V_m \ge V_{lth} \\ P_{pump} & \forall V_{lth} > V_m > V_{lb} \text{ and } P'_{HP} = P_{pump} + P_{booster} \\ 0 & \forall V_{lth} > V_m > V_{lb} \text{ and } P'_{HP} = P_{pump} \\ 0 & \forall V_m \le V_{lb} \end{cases} \quad (15)$$

3.2. Unified approach—complementing local voltage control with congestion management

The proposed unified approach complements the local voltage control with a centralized direct control based congestion management mechanism. Congestions caused by the increased load are managed by controlling the heat pump loads of the households. On the other hand, active power injection of the PV inverters is curtailed in case the reverse power flow exceeds the thermal rating of the transformer.

3.2.1. Direct control of the heat pumps

A number of mechanisms are reported in the literature to determine the switching actions of the directly controlled thermal loads [14,33,34]. A similar direct control method as discussed in Ref. [14], is applied in this work to reduce heat pump loads when a congestion in the transformer is detected. This is done by a merit-order based decision making scheme according to the inside temperature of the households and curtailment requests can be sent directly to the households with appropriate flexibility offers.

a. Flexibility offers

Different market-based mechanisms usually utilize additional market entities like aggregators, retailers and/or energy service companies (ESCos) to procure flexibility from residential end-users through local flexibility markets [35–38]. For instance, flexibility is often offered in terms of bids representing priorities and volumes of flexible power for certain monetary amounts. However, more direct approaches of curtailment are required if congestions occur when flexibility can no longer be procured by the market-based control.

In this work, a direct approach of load curtailment is investigated considering the temperature of the households. Being a direct approach, the process is coordinated by the DSO and tracking the inside temperature of the houses is not possible due to privacy concerns. The privacy bottleneck is circumvented using flexibility offers from the residential end-users. The flexibility offers represent the preferences of the consumers in terms of curtailable load and instantaneous thermal comfort [36,39] instead of the actual temperature. The comfort coefficient of i-th house at time t, $\rho_i{}^t$ can be defined as a function of actual and the maximum and minimum desirable limits of inside temperature (T_{max} and T_{min} respectively) of the house as,

$$\rho_i^t = \frac{T - T_{\min}}{T_{\max} - T_{\min}} \quad (16)$$

Based on the comfort coefficient, a flexibility offer is generated to inform the DSO about the curtailable load in the next time step. $\rho_{\min}$ being the minimum required level of comfort for providing network support, flexibility offer at time t, $F^t{}_i$ is given by,

$$F_i{}^t = \begin{cases} 0 & \forall \rho_i^t \le \rho_{\min} \\ P_{HP}^t - P_{pump} & \forall \rho_i^t > \rho_{\min} \& P_{HP}^t > P_{pump} \\ P_{pump} & \forall \rho_i^t > \rho_{\min} \& P_{HP}^t = P_{pump} \end{cases} \quad (17)$$

It is important to note that the households can utilize different modes of heat pump operations and can therefore choose an alternative approach of providing the flexibility offers.

b. Determining curtailment locations

The comfort coefficients and flexibility offers are collected by the DSO in each time step. A target loading level, S_{target} is considered in order to select suitable flexibility offers. Based on the available information, the DSO sends curtailment requests to appropriate connection points. In order to do so, the DSO aims to maximize the

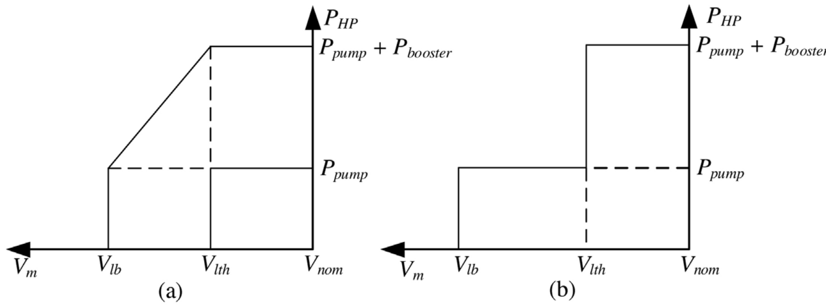

Fig. 2. Local undervoltage control with the heat pumps. (a) Linear droop control (b) step control.

comfort levels of the prosumers while maintaining the thermal constraints of the network. This can be expressed as an optimization problem as follows:

$$\min \sum_{i\in N,i=1}^{N} u_i.(1-\rho_i^t) \tag{18}$$

subject to,

$$u_i = \begin{cases} 1 & \text{if selected} \\ 0 & \text{if not selected} \end{cases} \tag{19}$$

$$\sum_{i\in N,i=1}^{N} u_i.F_i^t \le |S_{ins}^t| - |S_{target}| \tag{20}$$

where S_{ins}^t denotes the instantaneous transformer load at time, t.

Curtailment at each of the connection points is thus given by,

$$P_{curtail,i} = u_i.F_i^t \tag{21}$$

The decision variable, u_i is binary in nature in order to select the households for curtailing the heat pump loads. Thus, the optimization problem expressed by Eq. (18) can be solved by Mixed-Integer Programming (MIP) technique. Based on the solution, the DSO sends a curtailment request to the selected households. Upon receiving the request from the DSO, the heat pump controller limits its power consumption and supports the DSO with congestion management.

Apart from the outside temperature, the thermal mass of the household determines the change of temperature within the house. Thus, once a heat pump load is curtailed, the comfort coefficient starts decreasing gradually. At each discrete time step, transformer loading is observed and the curtailment requests are updated considering the new comfort levels of the households. It is important to note that, the heat pumps operate within a user-defined range of temperature and are switched on when the inside temperature reaches the lowest acceptable value. This ensures that the procured flexibility does not violate the comfort levels of the households. The process can be schematically presented as shown in Fig. 3.

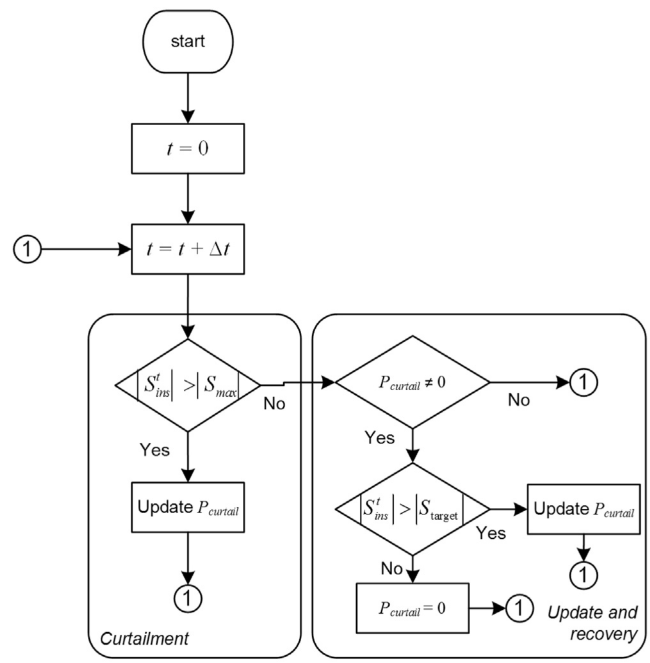

Fig. 3. Methodology of direct control of heat pumps for thermal constraint management.

3.2.2. Curtailment of active power injection of PV inverters

Active power curtailment of PV inverters has been the focus of a large body of literature. In addition to a number of market-based DR mechanisms, curtailment of injected active power has been studied to manage overvoltage and congestion problems [13,17,32,40]. Regulatory frameworks for curtailment and compensation of the curtailed power differs widely from country to country [5]. However, market-based control and consequent financial compensation are left out of the scope of this paper and residential consumers are considered for curtailment based on predefined bilateral agreements.

A fair curtailment scheme is adopted to limit the amount of injected power from the residential PV inverters to tackle the congestions caused by the reverse power flows. Total amount of required curtailment is calculated and distributed fairly among the inverters in the network considering individual injected energy. A curtailment coefficient, $w_{curtail,i}$ is used for the fair allocation of the curtailment and defined as the fraction of injected energy during each time step, Δt by the inverters to the total injected energy by all the inverters in the feeder.

$$w_{curtail,i} = \frac{E_{inj,i}}{\sum_{i\in N,i=1}^{N} E_{inj,i}} \tag{22}$$

where $E_{inj,i}$ denotes the injected amount of energy in kWh by the i-th of N households in the network. When congestion is detected, curtailment amount for each of the connection points is calculated considering a target level of transformer loading, S_{target}. Curtailment at each of the connection points, $P_{curtail,i}$ can thus be calculated by,

$$P_{curtail,i} = w_{curtail,i}.\left(|S_{ins}^t| - |S_{target}|\right) \tag{23}$$

The curtailment levels are reset to zero when the instantaneous loading, S_{ins}^t falls below S_{target}. The process can be schematically presented as shown in Fig. 4.

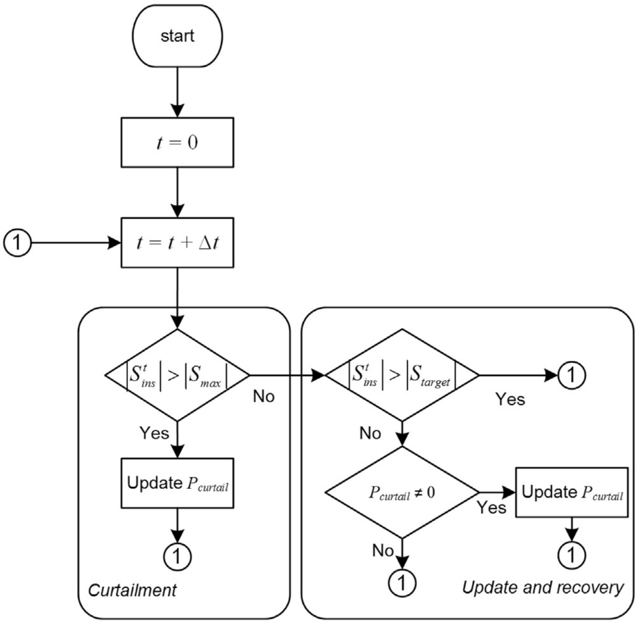

Fig. 4. Methodology of PV curtailment for thermal constraint management.

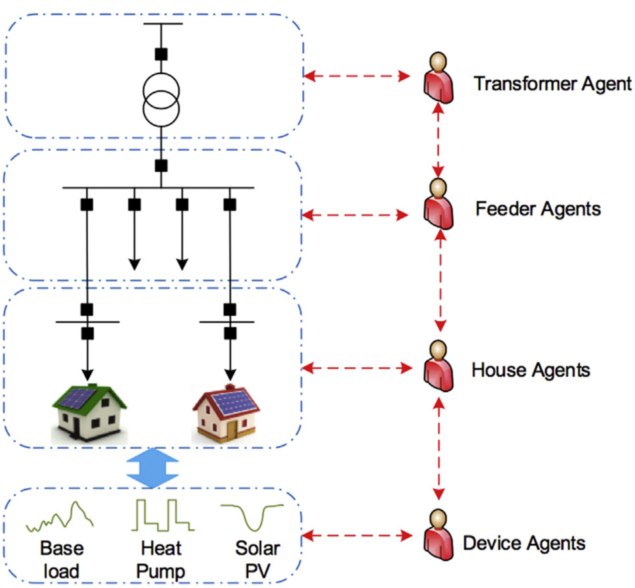

Fig. 5. MAS architecture of the unified approach.

4. Decentralized implementation

As highlighted in Section 3, the proposed unified approach constitutes of inter-operating centralized and decentralized systems with complex tasks. Computational and distributed intelligence has been discussed as a reliable, flexible and efficient tool to monitor and control such inter-operating systems. As a popular decentralized control approach, agent-based control has been extensively applied in electrical power and energy systems applications [2,21,41].

A Multi-Agent System (MAS)-based control scheme as shown in Fig. 5 has been developed to coordinate the process of the unified approach. Within each of the houses, the base load, PV inverter and heat pump are represented by individual device agents namely base load agent, PV agent and heat pump agent respectively. Each of the households is represented by a house agent (HA) that coordinates the device agents and works as the interface between the household and the external entities. The transformer agent (TA) and feeder agents (FA) correspond to the network agents and are responsible for monitoring the loading of the transformer and feeders respectively. The agents perform synchronous communication among them following the Agent Communication Language (ACL) standards. This makes the architecture easily scalable and interoperable with other network segments and market entities.

The HAs coordinate the device agents, as the device agents send relevant information such as consumed/generated power, voltage levels and temperature to the HA. Once a violation of the voltage levels is observed, the HA activates one of the local voltage control mechanisms instantaneously and keeps the voltage levels within acceptable margins. The HA calculates the comfort coefficients, corresponding flexibility offer and sends them along with the value of injected energy to the FA after every 15 min.

Each FA measures the power flow in the feeder and communicates with TA and the HAs. The TA checks the transformer loading conditions and communicates with the FAs. Once a congestion is detected, TA sends a curtailment request to the FAs. Next, the FA prepares a curtailment plan based on the comfort coefficients sent by the HAs and subsequently forward the request to the individual HAs.

In case the HA receives a curtailment request from the FA and also detects a voltage limit violations, it prioritizes the curtailment request sent by the FA and overrules the local control temporarily.

Contrary to a centralized method, the agent-based approach reduces the amount of information exchange and thereby lessens the required communication and computational burden. The computational intelligence integrated at the level of the FA and TA is capable of solving the problems with the locally available information. The approach is easily scalable and can be integrated with advanced market-based mechanisms to implement different demand response mechanisms. Moreover, flexibilities can also be procured to solve congestions at the MV networks through a flexibility request from the network agents located at the upper level, for instance in the MV feeders to the TA in the LV network.

Table 2
Parameters of the test network.

Property	Values
Transformer rating	10 kV/0.4 kV, 100 kVA
Transformer R0, Z0	0.0072 Ω, 0.0246 Ω
Power factor	0.98

5. Modelling and simulation

5.1. Test network

A typical Dutch residential LV network as shown in Fig. 6 is used as the test network for the simulation. The network comprises of 20 households and is fed from a 10/0.4 kV, 100 kVA MV/LV transformer. The network consists of underground power cables characterizing high R/X ratios compared to overhead lines. Properties of the test network are summarized in Table 2.

5.2. Simulation setup

Each of the households in the network is equipped with uncontrolled base loads, solar PV and domestic heat pumps. The base load profiles are shown in Fig. 7 and are modelled using average normalized profiles of 400 Dutch residential consumers [6,42]. The solar irradiation and the outdoor temperature data are obtained from the Royal Dutch Meteorological Institute (KNMI) [43]. The solar PV and heat pumps are modelled according to the functionalities

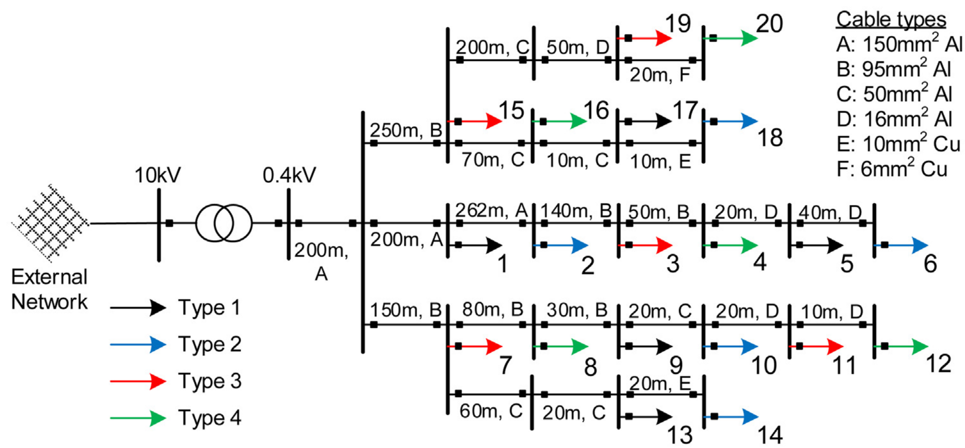

Fig. 6. Simulation test network.

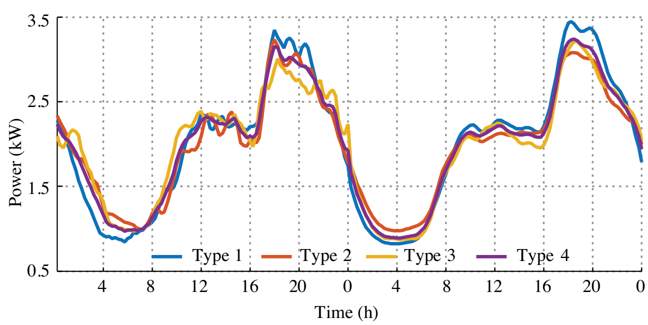

Fig. 7. Base load profiles used in the simulation.

Table 3
Properties of different heat pumps and thermal properties of the households.

Properties	Type 1	Type 2	Type 3	Type 4
Temperature range (°C)	19–21	19–22	18–21	18–22
P_{pump} (kW)	1.5	1.2	2	1.5
$P_{booster}$ (kW)	3	2.5	3	2.5
COP of HP	3.5	4	3	3.5
Internal heat gain (J)	400	200	500	350
UA (W/K)	270	300	400	150
Thermal capacity (MJ/K)	60.5	50.5	50.5	40.5
ρ_{min}	0.1	0.1	0.125	0.125
Installed PV capacity (kWp)	8.5	7.5	9.5	8

described in Refs. [3,44]. As shown in Table 3, four different types of heat pumps, household characteristics and installed PV capacities are considered and distributed among the 20 houses. A simplified thermal dynamics for the households is adopted assuming constant internal heat gain and heat loss due to transmission and ventilation only. COP and UA values denote the coefficient of performance of the HP unit and the thermal conductance of the households respectively. Assumed thermal capacities represent typical values for semi-detached Dutch households [44].

5.3. Simulation platform

The test network is modelled in Simulink/Matlab environment. The MAS architecture is implemented in JADE (Java Agent Development Framework) while the communication between two platforms is performed through TCP/IP as client-server. As shown in Fig. 8, based on the available information, each HA calculates and sends the comfort coefficient, injected energy and flexibility offers to the FA after every 15 min. In case of a voltage limit violation, the HA calculates the required amount of curtailment and sends a curtailment command back to the actuator modelled in Simulink.

After every 15 min, the TA checks the transformer loading and requests the FA for curtailment if congestion is detected. The FA coordinates the process of curtailment as discussed in Section 3.2 and sends resulting curtailment signals to the HAs. The curtailment signal is subsequently sent back to Simulink by respective HA to be implemented in the next time step.

6. Numerical results

Simulations are performed separately for two consecutive summer and a winter days in the Netherlands. The results of the case study are thus divided in two scenarios according to the seasonal variations as scenario A for summer and scenario B for winter.

6.1. Scenario A: summer

During summer, the solar PV generation in the households is coupled with the relatively low load demand and results in a considerable power injection from solar PV feeding into the network. This results in reverse power flows and local voltage rise toward the end of the radial LV feeder.

6.1.1. Local voltage control

Voltage levels at all the connection points in the network without any control mechanism are illustrated in Fig. 9. It is observed that the connection points located at the end of the feeders (e.g. house no. 6 and 20) experience higher voltage than the ones located closer to the transformer. The threshold of 1.06 p.u. is set for the sake of comparisons between control algorithms while the allowable upper limit of the voltage level is 1.1 p.u.

Voltage profiles of house nos. 6 and 20 are shown in Fig. 10 for both the local control mechanisms. The notable difference between the two control mechanisms occurs when the voltage levels exceed the threshold of 1.06 p.u. The droop control curtails the active power following the linear droop function and results in a slower voltage rise. On the other hand, the sensitivity-based control turns out to be a more conservative approach as it maintains the voltage levels closer to the threshold limit.

As can be seen from Fig. 11, injected active power from the PV inverters causes congestions in the transformer. Although local voltage control limits the power flow in the network during peak generation, the congestion is not fully resolved.

Amount of curtailed energy per household is shown in Fig. 12 as the percentage of generated PV energy. Unlike droop control, the sensitivity-based control curtails injected active power only

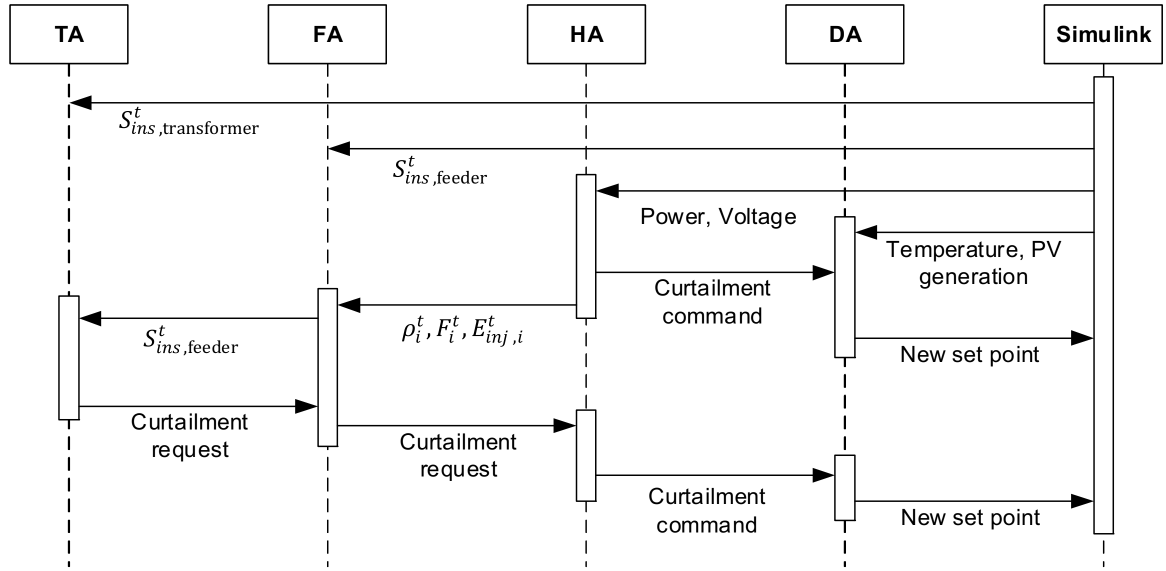

Fig. 8. UML sequence diagram of the simulation setup.

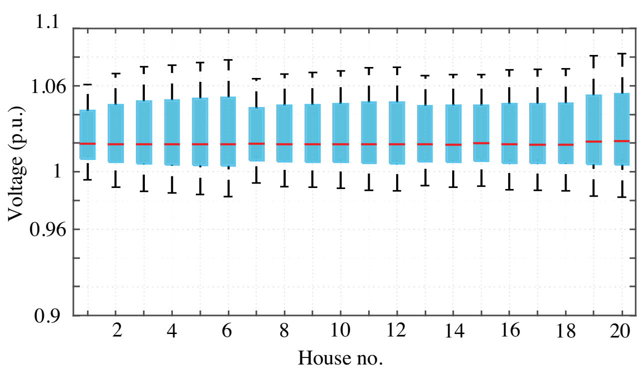

Fig. 9. Voltage levels at the connection points in summer.

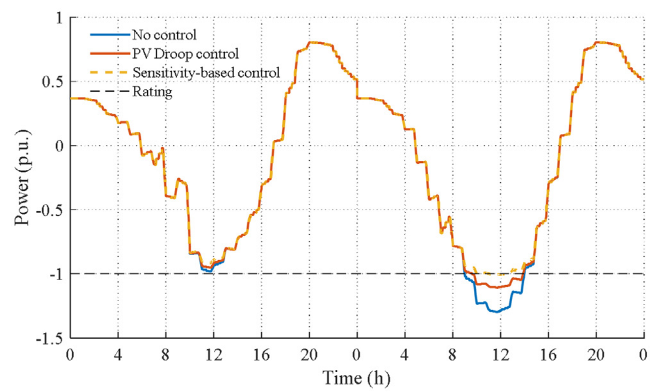

Fig. 11. Transformer loading with local control during summer.

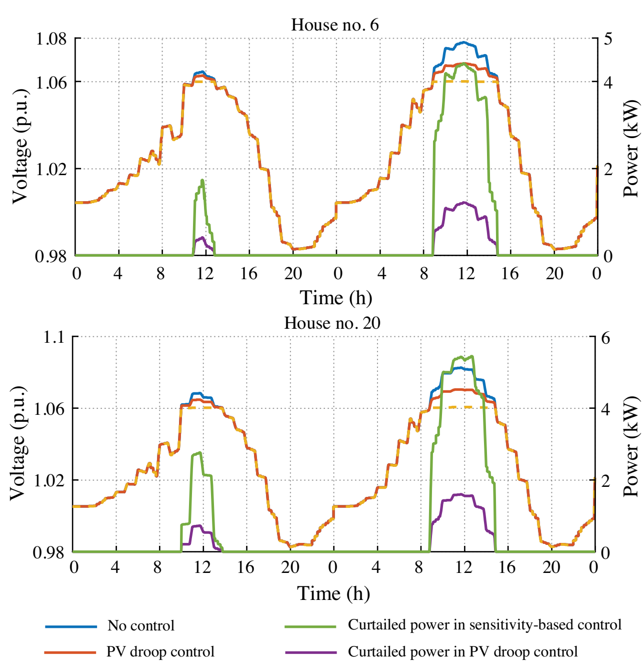

Fig. 10. Voltage profile and curtailed active power with local control at house nos. 6 and 20 in summer.

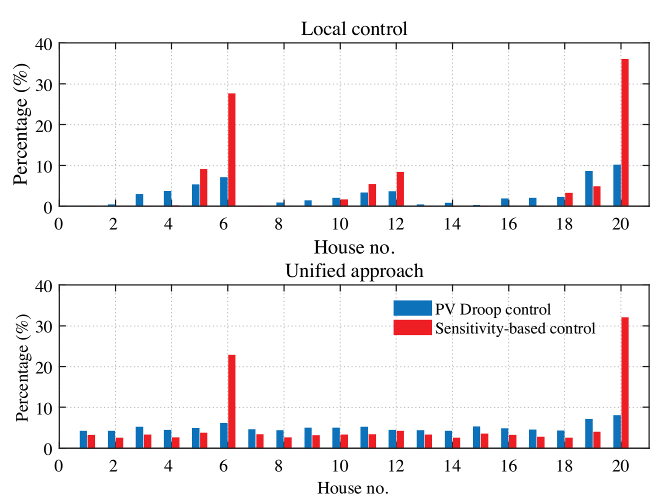

Fig. 12. Percentage of curtailed energy in summer.

at the houses located near the end of the feeder. The location of these houses attribute to a higher line resistance and stronger correlation between the voltage and active power. Consequently, voltage level violations occur at the end of the feeder predominantly earlier than the other connection points. On the contrary,

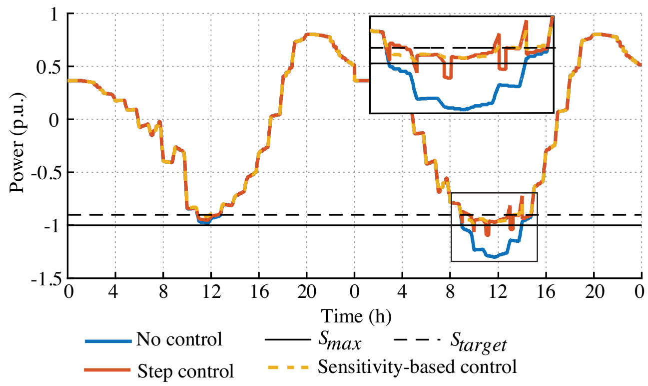

Fig. 13. Voltage levels at the connection points in winter.

the droop-control results in a relatively higher voltage profile and thus a lower amount of active power curtailment. Therefore, the threshold is not violated at the furthest connection points alone and PV generation is curtailed at other points as well. Both of the local control mechanisms result in an unfair PV curtailment among the connection points as the consumers located at the end of the feeder curtail considerably more active power than the others. A more centralized and coordinated voltage control mechanism is required to develop a fair basis of curtailment.

6.1.2. Unified approach

As depicted by the active power flow in the transformer in Fig. 13, the overloading of the transformer is largely mitigated with the unified approach. Apart from house nos. 6, 19 and 20, the percentage of the curtailed energy in case of the unified approach is mostly of the same order for all the connection points. This is due to the use of the curtailment coefficient that considers individual injected energy and fairly allocates the curtailment among the houses. For house nos. 6, 19 and 20, local voltage control entails more curtailment and thus overrules the request from the feeder agent.

Table 4 summarizes key results in terms of the maximum transformer load, duration of overloading and maximum voltage in the network. It is observed that, the unified approach effectively reduces the duration of overloading in the network as well as limits the voltage rise at the connection points. Compared to the local control, it also results in a lower curtailment for the connection points located at the end of a feeder section.

6.2. Scenario B: winter

Unlike the summer, the outside temperature in the winter is very low which introduces a high heating demand in the households. This, coupled with a low local PV generation leads to a higher loading in the feeder. Operational challenges thus occur in terms of local undervoltage problems along with the violation of thermal limits.

6.2.1. Local voltage control

As shown in Fig. 14, voltage levels during the winter day represent considerably lower magnitudes of voltages as compared to the summer case as several connection points experience violation of the threshold limit of 0.96 p.u.

Resulting voltage levels with the two undervoltage control methods for house nos. 6 and 20 are shown in Fig. 15. Although both of the methods can effectively mitigate the threshold violation, as illustrated in Fig. 16, the transformer congestion is not fully resolved. The notable difference between the two methods is that,

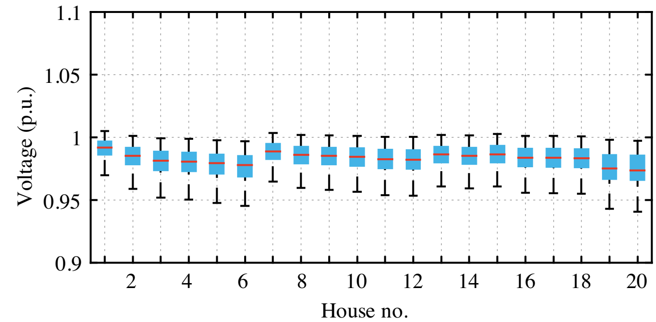

Fig. 14. Voltage profile with local control at house nos. 6 and 20 in winter.

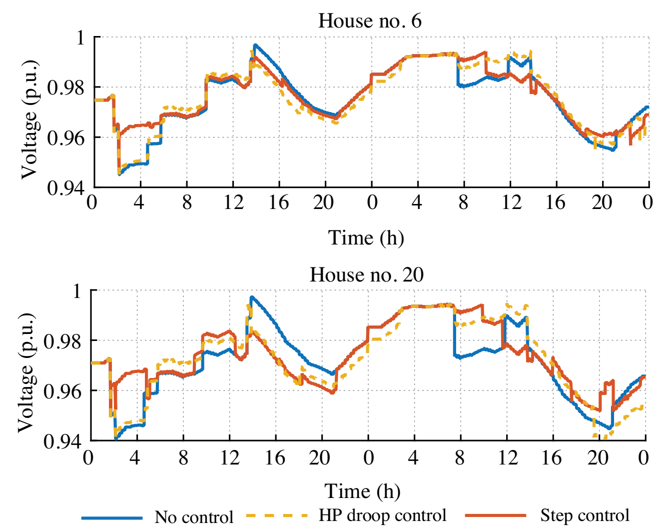

Fig. 15. Transformer load with unified approach in summer.

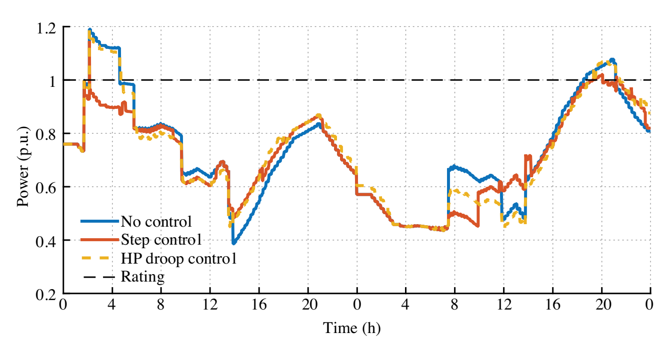

Fig. 16. Transformer load in winter with local control.

the step control involves a more conservative approach and results in a more improved voltage profile than linear droop control.

6.2.2. Unified approach

Transformer loading for the unified approach with both step and droop controls are illustrated in Fig. 17. Unlike the local control, in this case transformer load is reduced once it exceeds the nominal rating. However, the curtailed load necessitates to be supplied again to maintain the thermal comfort of the consumers. The increased feeder load exceeds the threshold and heat pump loads are once again curtailed.

A number of performance metrics for the proposed approaches along with the case of no control are summarized in Table 5. It is evident that even though the proposed mechanisms work on the basis of curtailing loads, loads are merely shifted from one time

Table 4
Summarized results for scenario A.

Properties	No control	Local control		Unified approach	
		PV droop	Sensitivity-based	PV droop	Sensitivity-based
Maximum voltage (p.u.)	1.082	1.070	1.062	1.070	1.061
Maximum load (p.u.)	1.23	1.11	1.00	1.09	1.00
Overload duration (h)	4.98	4.26	1.48	0.61	0.00

Table 5
Summarized results for scenario B.

Properties	No control	Local control		Unified approach	
		Step control	HP droop	Step control	HP droop
Energy supplied (MWh)	4.80	4.70	4.78	4.68	4.72
Curtailed energy (%)	–	2.08	0.35	2.51	1.72
Minimum voltage (p.u.)	0.941	0.956	0.948	0.947	0.942
Maximum load (p.u.)	1.19	1.15	1.19	1.15	1.19
Duration of overloading (min)	305.75	50.52	288.35	0.03	12.02
Average consumption per household (kWh)	167.56	164.17	166.96	163.46	164.70

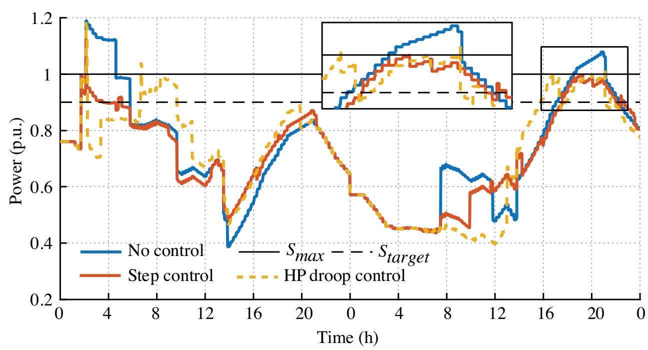

Fig. 17. Transformer load in the winter with unified approach.

instant to another in order to maintain the voltage levels and tackle congestion. Compared to the linear droop control, step control curtails more energy but results in a much improved performances as the total duration of overloading is largely mitigated. As expected, the unified approach curtails more load and the total duration of overloading is mostly negligible.

Fig. 18 depicts the consumption profile of the heat pump at house no. 20 along with the inside temperature of the house for local control and unified approach. As can be seen from Fig. 18(a), the droop control limits the consumption of the resistive heating element, ($P_{booster}$) while the step control switches it off. This is reflected in the temperature as droop control results in a slightly flatter slope compared to the case with no control. Due to the heat loss from the building, step control results in a reduction of the inside temperature and the heat pump is switched back again after a few hours when the temperature reaches the lower threshold of 18 °C. On the contrary, the unified approach curtails the heat pump load when congestion is detected even after local control starts regulating the voltage levels. The profile for the step control remains same for both of the cases as the local control can already lower the transformer loading by a considerable margin.

The impact of the control methodologies is investigated in terms of the deviation in the mean temperature for the cases of local control and unified approach from the mean temperature with no control. As illustrated in Fig. 19, mean temperature inside the

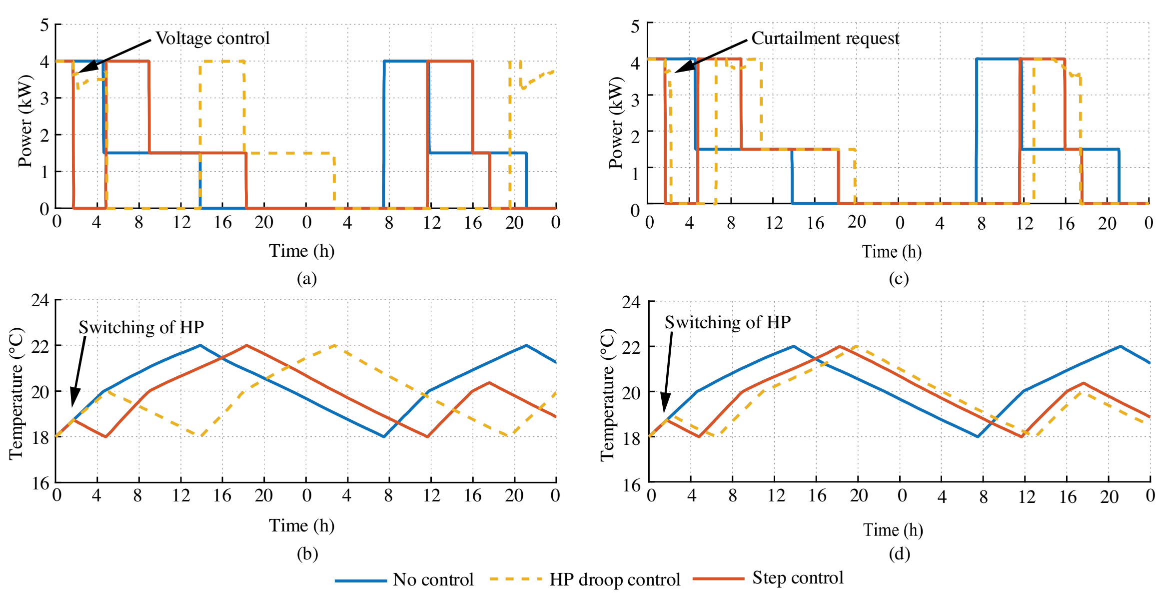

Fig. 18. HP consumption profiles and corresponding internal temperature at house nos. 20. (a) Consumption with local control, (b) temperature with local control, (c) consumption with unified approach, (d) temperature with unified approach.

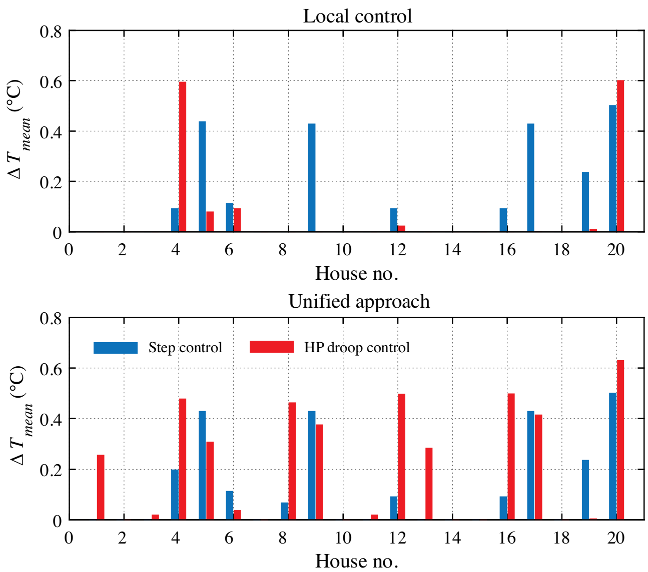

Fig. 19. Deviation in mean inside temperature from mean temperature with no control.

households becomes lower due to the curtailment of the heat pump loads. In case of the local voltage control, step control results in deviations in more households, as the droop control curtails only part of the resistive heater power. In contrast, the unified approach curtails the loads when congestion is detected in the MV/LV transformer. Consequently, more households experience curtailment leading to lower average temperature. It needs to be noted that, the heat pumps continue maintaining the inside temperature within the predefined set points even though the mean temperature is reduced due to curtailment.

7. Conclusions

In this study, we propose a unified control approach to manage simultaneously network congestions and local voltage limit violations in LV radial distribution networks. The proposed approach utilizes advanced active power curtailment mechanisms with a MAS-based system architecture. This scalable and distributed platform allows to integrate both centralized congestion management and decentralized voltage control mechanisms. Simulation results for a Dutch LV network with full penetration of solar PV and heat pumps indicate that the proposed approach can effectively tackle both overvoltage and undervoltage problems along with the congestions of the MV/LV transformer.

Utilizing the MAS-based system architecture in this proposed approach opens also a possibility to integrate different market-based control mechanisms. This can help to identify the probable challenges that come with the integration of other DERs along with different market entities.

Acknowledgements

The authors would like to thank the Universal Smart Grids Energy Framework and EU FP7 project INCREASE for the support in the research.

References

[1] J. Ekanayake, N. Jenkins, K. Liyanage, J. Wu, A. Yokoyama, Smart Grid: Technology and Applications, John Wiley & Sons, Ltd., Chichester, UK, 2012, http://dx.doi.org/10.1002/9781119968696.
[2] P.H. Nguyen, Multi-Agent System Based Active Distribution Networks, Eindhoven University of Technology, 2010 http://alexandria.tue.nl/extra2/693215.pdf.
[3] B. Asare-Bediako, W.L. Kling, P.F. Ribeiro, Future residential load profiles: scenario-based analysis of high penetration of heavy loads and distributed generation, Energy Build. 75 (2014) 228–238, http://dx.doi.org/10.1016/j.enbuild.2014.02.025.
[4] E. Veldman, R.A. Verzijlbergh, Distribution grid impacts of smart electric vehicle charging from different perspectives, Smart Grid IEEE Trans. 6 (2015) 333–342, http://dx.doi.org/10.1109/TSG.2014.2355494.
[5] Eurelectric, Active distribution system management a key tool for the smooth integration, 2013. http://www.eurelectric.org/media/74346/asm_final_generis_recomm_130204_def_lr-2013-030-0116-01-e.pdf.
[6] E. Veldman, Power Play—Impacts of Flexibility in Future Residential Electricity Demand on Distribution Network Utilisation, Eindhoven University of Technology, 2013.
[7] R.A. Verzijlbergh, L.J. De Vries, Z. Lukszo, Renewable energy sources and responsive demand. Do we need congestion management in the distribution grid? IEEE Trans. Power Syst. 29 (2014) 2119–2128, http://dx.doi.org/10.1109/TPWRS.2014.2300941.
[8] A.N.M.M. Haque, P.H. Nguyen, W.L. Kling, Capacity management in a generalized smart grid framework, Proceedings of the IEEE Young Researchers Symposium (YRS 2014) (2014) 1–5, http://dx.doi.org/10.13140/RG.2.1.4555.2727.
[9] A.N.M.M. Haque, P.H. Nguyen, W.L. Kling, F.W. Bliek, Congestion management in smart distribution network, Power Eng. Conf. (UPEC), 2014 49th Int. Univ. (2014) 1–6, http://dx.doi.org/10.1109/UPEC.2014.6934751.
[10] I. Bilibin, F. Capitanescu, Contributions to thermal constraints management in radial active distribution systems, Electr. Power Syst. Res. 111 (2014) 169–176, http://dx.doi.org/10.1016/j.epsr.2014.02.018.
[11] T. Sansawatt, L.F. Ochoa, G.P. Harrison, Smart decentralized control of DG for voltage and thermal constraint management, IEEE Trans. Power Syst. 27 (2012) 1637–1645, http://dx.doi.org/10.1109/tpwrs.2012.2186470.
[12] H.P. Simão, H.B. Jeong, B. Defourny, W.B. Powell, A. Boulanger, A. Gagneja, et al., A robust solution to the load curtailment problem, IEEE Trans. Smart Grid. 4 (2013) 2209–2219, http://dx.doi.org/10.1109/TSG.2013.2276754.
[13] N. Etherden, M.H.J. Bollen, Overload and overvoltage in low-voltage and medium-voltage networks due to renewable energy—some illustrative case studies, Electr. Power Syst. Res. 114 (2014) 39–48, http://dx.doi.org/10.1016/j.epsr.2014.03.028.
[14] S. You, H. Segerberg, Integration of 100% micro-distributed energy resources in the low voltage distribution network: a Danish case study, Appl. Therm. Eng. 71 (2) (2014) 797–808, http://dx.doi.org/10.1016/j.applthermaleng.2013.11.039, ISSN 1359-4311.
[15] A.N.M.M. Haque, T. Rahman, P.H. Nguyen, F.W. Bliek, Smart curtailment for congestion management in LV distribution network, in: IEEE PES Gen. Meet., Boston, USA, 2016, pp. 1–5.
[16] T. Sansawatt, L.F. Ochoa, G.P. Harrison, Integrating distributed generation using decentralised voltage regulation, Power and Energy Society General Meeting, 2010 IEEE (2010) 1–6, http://dx.doi.org/10.1109/PES.2010.5588127.
[17] M.M. Viyathukattuva, M.A.P.H. Nguyen, W.L. Kling, An integrated control for overvoltage mitigation in the distribution network, IEEE PES Innovative Smart Grid Technologies Conference Europe (2014) 1–6, http://dx.doi.org/10.1109/ISGTEurope.2014.7028903.
[18] R. Tonkoski, L.A.C. Lopes, Droop-based active power curtailment for overvoltage prevention in grid connected PV inverters, IEEE International Symposium on Industrial Electronics (ISIE) (2010) 2388–2393, http://dx.doi.org/10.1109/ISIE.2010.5637511.
[19] K. Christakou, J.-Y. LeBoudec, M. Paolone, D.-C. Tomozei, Efficient computation of sensitivity coefficients of node voltages and line currents in unbalanced radial electrical distribution networks, IEEE Trans. Smart Grid 4 (2013) 741–750, http://dx.doi.org/10.1109/tsg.2012.2221751.
[20] P.M.S. Carvalho, P.F. Correia, L.A.F. Ferreira, Distributed reactive power generation control for voltage rise mitigation in distribution networks, IEEE Trans. Power Syst. 23 (2008) 766–772, http://dx.doi.org/10.1109/tpwrs.2008.919203.
[21] L.A. Hurtado, P.H. Nguyen, W.L. Kling, Smart grid and smart building inter-operation using agent-based particle swarm optimization, Sustain. Energy Grids Netw. 2 (2015) 32–40, http://dx.doi.org/10.1016/j.segan.2015.03.003.
[22] A. Engler, N. Soultanis, Droop control in LV-grids, 2005 International Conference on Future Power Systems, IEEE (2005), http://dx.doi.org/10.1109/FPS.2005.204224, p. 6 pp.-pp. 6.
[23] P. van Oirsouw, Ontwerpen van distributienetten, Netten Voor Distrib. van Elektr., Phase to Phase B.V., Arnhem (2011) 571–608.
[24] S. Huang, Q. Wu, Z. Liu, A.H. Nielsen, Review of congestion management methods for distribution networks with high penetration of distributed energy resources, IEEE PES Innovative Smart Grid Technologies Conference Europe, IEEE (2014) 1–6, http://dx.doi.org/10.1109/ISGTEurope.2014.7028811.
[25] A.N.M.M. Haque, P.H. Nguyen, W.L. Kling, Congestion management with the introduction of graceful degradation, in: PowerTech, 2015 IEEE Eindhoven, Eindhoven, Netherlands, 2015, pp. 1–6, http://dx.doi.org/10.1109/PTC.2015.7232806.
[26] P. Bach Andersen, J. Hu, K. Heussen, Coordination strategies for distribution grid congestion management in a multi-actor, multi-objective setting, 2012

3rd IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe) (2012) 1–8, http://dx.doi.org/10.1109/ISGTEurope.2012.6465853.
[27] A.S. Masoum, S. Deilami, P.S. Moses, M.A.S. Masoum, A. Abu-Siada, Smart load management of plug-in electric vehicles in distribution and residential networks with charging stations for peak shaving and loss minimisation considering voltage regulation, IET Gener. Transm. Distrib. 5 (2011) 877, http://dx.doi.org/10.1049/iet-gtd.2010.0574.
[28] T. Xu, P.C. Taylor, Voltage control techniques for electrical distribution networks including distributed generation, IFAC Proceedings Volumes 41 (2) (2008) 11967–11971, ISSN 1474-6670 http://dx.doi.org/10.3182/20080706-5-KR-1001.02025.
[29] R. Yan, T.K. Saha, Investigation of voltage variations in unbalanced distribution systems due to high photovoltaic penetrations, in: 2011 IEEE Power and Energy Society General Meeting, San Diego, CA, 2011, pp. 1–8, http://dx.doi.org/10.1109/PES.2011.6038977.
[30] M.Z. Degefa, M. Lehtonen, R.J. Millar, A. Alahäivälä, E. Saarijärvi, Optimal voltage control strategies for day-ahead active distribution network operation, Electr. Power Syst. Res. 127 (2015) 41–52, http://dx.doi.org/10.1016/j.epsr.2015.05.018.
[31] T.L. Vandoorn, J.D.M. De Kooning, B. Meersman, L. Vandevelde, Soft curtailment for voltage limiting in low-voltage networks through reactive or active power droops, 2012 IEEE International Energy Conference and Exhibition (ENERGYCON) (2012) 545–550, http://dx.doi.org/10.1109/EnergyCon.2012.6348213.
[32] R. Tonkoski, L.A.C. Lopes, Impact of active power curtailment on overvoltage prevention and energy production of PV inverters connected to low voltage residential feeders, Renew. Energy 36 (2011) 3566–3574, http://dx.doi.org/10.1016/j.renene.2011.05.031.
[33] M. Babar, T.P.I. Ahamed, E. Al-Ammar, A. Shah, Consolidated demand bid model and strategy in constrained Direct Load Control program, 2015 IEEE 8th GCC Conference and Exhibition (GCCCE) (2015) 1–4, http://dx.doi.org/10.1109/IEEEGCC.2015.7060013.
[34] Clearly Energy, Residential demand response programs, (n.d.). https://www.clearlyenergy.com/residential-demand-response-programs (Accessed 8 July 2016).
[35] F. Bliek, A. Backers, M. Broekmans, C. Groosman, H. de Heer, M. van der Laan, et al., An introduction to the Universal Smart Energy Framework, USEF 2014 (2014), http://dx.doi.org/10.13140/2.1.2275.1046.
[36] J.A.W. Greunsven, E. Veldman, P.H. Nguyen, J.G. Slootweg, I.G. Kamphuis, Capacity management within a multi-agent market-based active distribution network, IEEE PES Innovative Smart Grid Technologies Conference Europe (2012) 1–8, http://dx.doi.org/10.1109/ISGTEurope.2012.6465678.
[37] K. Kok, The PowerMatcher: Smart Coordination for the Smart Electricity Grid, Vrije Universiteit Amsterdam, 2013 http://medcontent.metapress.com/index/A65RM03P4874243N.pdf.
[38] A.N.M.M. Haque, D.S. Shafiullah, P.H. Nguyen, F.W. Bliek, Real-time congestion management in active distribution network based on dynamic thermal overloading cost, 2016 Power Systems Computation Conference (2016) 1–7, http://dx.doi.org/10.1109/PSCC.2016.7540985.
[39] R. Westerga, L. Bakker, K. Helmholt, F. Rumph, T. Thijssen, Regelruimte Warmtepompen—Proof of Principle (update), 2011.
[40] M.S.H. Nizami, A.N.M.M. Haque, P.H. Nguyen, F.W. Bliek, HEMS as network support tool: facilitating network operator in congestion management and overvoltage mitigation, in: 2016 IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC), Florence, 2016, pp. 1–6, http://dx.doi.org/10.1109/EEEIC.2016.7555678.
[41] J. Hu, A. Saleem, S. You, L. Nordström, M. Lind, J. Østergaard, A multi-agent system for distribution grid congestion management with electric vehicles, Eng. Appl. Artif. Intell. 38 (2015) 45–58, http://dx.doi.org/10.1016/j.engappai.2014.10.017.
[42] Energie Data Services Nederland, (n.d.). http://www.edsn.nl/.
[43] Koninklijk Nederlands Meteorologisch Instituut, (n.d.). http://www.knmi.nl/home (Accessed 7 January 2016).
[44] B. Asare-bediako, SMART Energy Homes and the Smart Grid, University of Technology, Eindhoven, 2014.