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Demand response for real-time congestion management incorporating dynamic thermal overloading cost

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HIGHLIGHTS

- Determination of a dynamic thermal overloading cost.
- Design of a demand response methodology for real-time congestion management.
- Agent-based distributed intelligence to solve the congestions locally.
- Local flexibility market to procure flexibility in a multi-actor setting.

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ABSTRACT

Capacity challenges are emerging in the low-voltage (LV) distribution networks due to the rapid proliferation of distributed energy resources (DERs) and increasing electrification of loads. The traditional approach of network reinforcement does not achieve the optimal solution due to the inherent uncertainties associated with the DERs. In this article, a methodology of real-time congestion management of MV/LV transformers is proposed. A detailed thermal model of the transformer is used in order to obtain the costs incurred by overloading. An agent-based scalable architecture is adopted to combine distributed with computational intelligence for the optimum procurement of flexibility. The efficiency of the proposed mechanism is investigated through network simulations for a representative Dutch LV network. Simulation results indicate that the methods can effectively alleviate network congestions, while maintaining the desired comfort levels of the prosumers.

1. Introduction

Driven by an effective international climate policy [1,2], the electrical distribution networks worldwide have been hosting an increasing share of renewable energy resource (RES) based distributed generation (DG) and new forms of load consumption such as electric vehicles (EVs), heat pumps (HPs), or electrical heating ventilation and air-conditioning (HVAC) systems. Along with a greener energy mix, these Distributed Energy Resources (DERs) bring forth operational challenges including voltage violations or thermal overloading of network assets [3,4]. Consequently, distribution system operators (DSOs) require to enhance monitoring and control ability in the network and a shift towards Active Distribution Networks (ADNs) becomes imminent [5–7].

Congestions or thermal overloadings occur when the power flow through a network asset (e.g. lines, cables, transformers) exceeds its transfer capability. Although the network assets are generally designed to withstand loads beyond a certain margin, continuous overloading results in degradation of the insulation of the distribution cables and transformer windings [8,9]. The traditional approach of reinforcing the network assets in such cases, not only necessitates a huge investment, but will also be deemed redundant as the peak loads tend to appear only for few hours in a year [3]. To circumvent the required investment, a number of direct and indirect control approaches have been studied to tackle congestion issues in the ADNs. While the direct approaches mitigate congestions by curtailment of load and local generation [10,11], or by influencing the voltage level at the secondary side of a smart MV/LV transformer [12,13], their indirect counterparts motivate individual prosumers with

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Nomenclature

Indices

λ	Index for internal control signal
a	Index for aggregators
f	Index for feeder clusters
h	Index for houses
i	Index for flex offers
j	Index for flexibility request
k	Index for devices
t	Index for time step

Parameters

$\Delta\theta^{HR}$	Hottest-spot temperature rise at rated load
$\Delta\theta^{TR}$	Top-oil temperature rise at rated load
N_a^f	Number of feeder clusters for ath aggregator
N_f^h	Number of houses in fth feeder cluster
N_a	Number of aggregators
N_d	Length of the flexibility request bid
N_h	Number of houses
N_k	Number of devices
S_{rated}	Transformer nominal rating

Variables

$\Delta\lambda$	Price adjustment
$\Delta\theta_t^H$	Hottest-spot temperature rise at time t
$\Delta\theta_t^{TO}$	Top-oil temperature rise at time t
λ_a^*	Internal price signal for aggregator a
Φ_t^{AA}	Ageing acceleration factor at time t
Φ_t^{eq}	Equivalent factor at time t
θ_λ^H	Hottest-spot temperature for λ
C_t^{DA}	Day-ahead electricity price for time t
C^{OL}	Overloading cost
d	Bids
d_{af}^{flex}	Flex bid of fth feeder cluster of ath aggregator
F_{af}	Flex offer of fth feeder cluster of ath aggregator
L_t^e	Total expected load at time t
N_{af}^F	Number of flex offers in fth feeder cluster of ath aggregator
T_t^{lol}	Loss of life at time t
u_{af}	Binary decision variable for selecting feeder cluster
x_{af}^i	Binary decision variable for selecting ith flex offer of feeder cluster

appropriate price and/or incentive-based Demand Response (DR) mechanisms [14,9]. The price-based methods include day-ahead dynamic tariff, distribution grid capacity market, intra-day shadow price, flexibility service market, etc. However, most of these mechanisms aim to influence the demand flexibility only, while neglect or partially address physical constraints of the distribution networks [15–17]. Consequently, applications of the DR-based methods for managing real-time congestions are still quite limited.

Different types of multi-agent system (MAS) based DR mechanisms have been deployed to exploit the flexibility from the small-scale prosumers [18–21]. As highlighted in [21–23], the agent-based PowerMatcher technology optimizes the potential for aggregated individual household devices to adjust real-time operation. At the same time, Universal Smart Energy Framework (USEF) has been recently introduced as a conceptual approach to manage congestions more efficiently [24,9,25]. USEF combines the indirect and direct approaches of congestion management to enhance the flexibility in the distribution network and enables the DSO to obtain flexibility from a local capacity market to relieve network congestions. A more direct approach of graceful degradation complements the market-based control to curtail active power demand when adequate flexibility is not available in the market.

However, for a market-based DR mechanism, a sound methodology for real-time congestion management is significant in order to transform the realized ageing of the network assets to a corresponding monetary loss. Based on the recent developments, an integrated congestion management mechanism is proposed in [9] for the residential distribution network incorporating dynamic thermal overloading model of a distribution transformer. However, in reality, procurement of flexibility in real-time appears to be a more complex problem involving scenarios with multiple market entities in the same congested network area [26]. This work extends the market-based control proposed in [9] further, incorporating computational intelligence in a multi-actor setting. The method will take advantages of the scalable architecture of the agent-based DR technology and detailed thermal model of oil-immersed transformers. A detailed case-study, involving 229 households is presented to illustrate the impacts and expected results of the proposed mechanism. The main scientific contributions of the paper are as follows:

- Demand response methodology incorporating the overloading cost, calculated from the dynamic thermal model of the transformer.
- Application of agent-based distributed intelligence to solve the congestions locally.
- An appropriate local flexibility market to procure flexibility in a multi-actor setting.

The remainder of the paper is organized as follows: Section 2 presents the overview of the market-based control, Section 3 describes the thermal loading model of the transformer, the methodology of flexibility procurement is detailed in Section 4, while Section 5 provides the description of the test scenario and the assumptions adopted. Finally, simulation results are presented and analysed in Section 6, before summarizing and concluding with Section 7.

2. Market-based control in distribution network

2.1. Flexibility in distribution network operations

Due to the increasing availability of the flexible domestic appliances and small-scale generation technologies like rooftop solar PV, market-based control of the distribution network has been drawing an extensive attention of late [27–29]. Apart from introducing new market entities such as aggregators and energy service companies, this has principally paved the way for a more decentralized operation of the future power system.

Different types of flexibility arrangements have been discussed in the literature with varied scopes and aims ranging from balancing services [28,30–32] to network congestion management [33,27,34]. In this regard, price-based and incentive-based DR programs have been widely studied to invoke demand flexibility available in the network. A number of locational marginal pricing (LMP) methods have also been proposed for solving congestions based on day-ahead electricity market price [27,35]. Recently, local flexibility markets have also been proposed in order to facilitate a convenient interaction among the aggregators providing flexibility and the network operators who need the flexibility for network operations [36].

In this research, we develop a mechanism for real-time procurement of flexibility for congestion alleviation in LV distribution networks considering the incurred cost due to congestion. A bottom-up approach is adopted for modelling the loads of the residential prosumers. An agent-based system architecture is chosen for