Real-Time Congestion Management in Active Distribution Network based on Dynamic Thermal Overloading Cost

A.N.M.M. Haque*, D.S. Shafiullah, P.H. Nguyen  
Department of Electrical Engineering  
Eindhoven University of Technology  
5600 MB Eindhoven, The Netherlands  
E-mail*: a.n.m.m.haque@tue.nl

F.W. Bliek  
DNV GL Energy  
9704 CA Groningen, The Netherlands

Abstract— The rapid proliferation of distributed energy resources (DERs) leads to capacity challenges, i.e. network congestions, in the low-voltage (LV) distribution networks. Different types of control strategies are being developed to tackle the challenges with direct switching actions such as load shedding or power curtailment. Alternatively, demand flexibility from the large number of DERs is being considered as a potential approach by influencing the individual end-users with various demand response (DR) programs. However, most of the DR-based solutions focus on scheduling phase, thus having a limitation to handle network issues in real-time grid operation. In order to improve DR’s capability, besides a proper incentive scheme for involved actors, the DR-based approach needs to integrate network constraints and quantify this real-time information in its control process. In this paper, a novel method for real-time congestion management is proposed, which focuses on resolving the congestion problem at the MV/LV transformer. Detail models for different loads and thermal overloading of the MV/LV transformer are developed to realize the benefits of the demand flexibility. The overall performance of the integrated approach for the congestion management has been verified by a simulation with a typical LV network of the Netherlands.

Index Terms— Congestion management, graceful degradation, thermal overloading, overloading cost.

I. INTRODUCTION

The electrical distribution network is gradually moving towards an actively controlled system which has been mostly passive in nature [1], [2]. This paradigm shift to the Active Distribution Network (ADN) concept is being accelerated by the increasing share of renewable energy sources (RES) and new forms of load consumption such as electric vehicles (EVs), heat pumps (HPs), or electrical heating ventilation and air-conditioning (HVAC) systems. The intermittent and unpredictable nature of these Distributed Energy Resources (DERs) introduce operational challenges for the network operators in terms of voltage limit violations or thermal overloading (congestion) of network components. Different distribution system operators (DSOs) in Italy, Spain, Ireland and Germany with large share of installed DGs and with long feeder lengths experience voltage limit violations in their networks [3].

Meanwhile, network congestions can be a further critical issue in more densely clustered networks like in the Netherlands [3]–[5]. A projected growth of the Dutch electricity network, as presented in [6] shows that with future load growth and new generation technologies, 87% of the HV/MV transformers will be overloaded compared to only 34% of the distribution cables in 2040. Reinforcing these network assets necessitates huge amount of investment although the peak loads will generally occur only for few hours in a year [6].

In the conventional scenario, generation or demand curtailment has been used in cases of system reliability related events. This leads to interruptions of a large number of connected end-users and takes a long time to restore to the normal operations [7]. From the literature, the congestion management techniques can be roughly subdivided into two categories namely, direct and indirect control approaches [8]. The direct control approach aims to mitigate the congestions by curtailment of load and local generation while the indirect approach influences the individual prosumers with price and/or incentive based Demand Response (DR) mechanisms. Among the direct approaches, a centralized congestion management mechanism is proposed in [9] that uses remotely controlled switches or breakers to curtail the non-firm DG in a radially operated LV distribution network. A case-study in the Danish LV network is presented in [10] with full penetration of HPs and EVs. It is pointed out that a simple merit-order based system is sufficient to deal with local congestions in distribution cables. A ‘hosting capacity’ based curtailment mechanism is presented in [11] to relieve congestions from the RES-based generation technologies. Meanwhile, various price-based methods such as day-ahead dynamic tariff, distribution grid capacity market, intra-day shadow price, flexibility service market represent the indirect DR-based methods [8]. However, most of these mechanisms focused only on employing the demand flexibility in general, while neglect or partially address physical constraints of the distribution networks [5].
Therefore, applications of the DR-based methods to handle real-time network congestion issues are still quite limited.

In the Netherlands, attempts have been made to utilize the flexibility from the large number of small-scale prosumers by introducing different agent-based DR solutions [12]–[14]. This technology optimizes the potential for aggregated individual electricity producing and consuming devices to adjust their real-time operation. In a complement development, Universal Smart Energy Framework (USEF) has been recently introduced as a conceptual approach to manage congestion in the distribution network more efficiently [15]. USEF aims to inherently combine the indirect and direct approaches of congestion management to enhance the flexibilities in the distribution network. This framework enables the DSO to procure flexibility from a local capacity market to resolve the congestion, while graceful degradation is activated to limit network access in terms of connection capacities. This assists the DSO to maintain the network reliability even when sufficient flexibility is not available in the network.

This paper focuses on the development of a novel integrated congestion management mechanism in the residential distribution network incorporating dynamic thermal overloading model of a distribution transformer. The method will take advantages of the scalable architecture of the agent-based DR technology as well as advanced power curtailment mechanisms to resolve congestion. The following sections discuss the background information, system architecture along with the detailed methodologies. A case-study is also presented to illustrate the impacts and expected results of the proposed mechanism.

II. BACKGROUND

In this paper, the proposed solution for congestion management is developed on the basis of the framework of USEF. The primary objective is to invoke the flexibility available from the small-scale active prosumers, i.e. end-users and local producers, to improve system demand-supply balance as well as network reliability [15]. Development of USEF enables the DSOs to manage the congestions through an active and integrated mechanism. Regarding network issues such as voltage violation or current congestions, USEF distinguishes two different grid operating regimes to increase the effective use of network assets as follows:

- Yellow operating regime: DSOs can procure demand flexibility from an (independent) aggregator to resolve network issues;
- Orange operating regime: DSOs must limit connection capacities if the demand flexibility is not sufficient to resolve network issues. This is known as graceful degradation process.

The following sub-sections elaborate more in detail about different DR solutions that can be coupled in the yellow operating regime as well as challenges for the development of graceful degradation.

A. DR solutions to tackle network issues

Within the yellow operating regime, different DR solutions can be deployed, by either through prearranged bilateral contracts or through a local flexibility market. The application of DR mechanisms can enhance grid operation by scheduling the flexible loads to a different time in order to avoid congestion. The possibility of shifting the loads in time has contributed to the development of DR programs through different types of market-based control mechanisms to relieve congestions in the distribution networks. These include dynamic network tariff, time-of-use (ToU) pricing, advanced capacity allocation, distribution grid capacity market etc. [16]. These ideas essentially aim to influence the individual prosumers in the network to respond to the price signals in order to shift their flexible demands to the time instances where the price of electricity is relatively lower.

As aforementioned, PowerMatcher has been developed as an efficient DR platform that allows the individual prosumers to actively participate in the energy market by responding to real-time internal price signals. This agent-based application is designed to coordinate a cluster of DERs by using an electronic energy exchange market with one of the objectives to match the supply and demand of the respective cluster [14]. In the PowerMatcher, the DERs are represented by software agents, which optimize the main objective of the respective devices. Detailed description and mechanisms related to PowerMatcher can be found in [14].

B. Graceful degradation by active power curtailment

In exceptional situations where the flexibility market is no longer able to maintain the network loading and voltage levels within acceptable limits, USEF compliant systems switch to the orange regime by starting the process of so-called graceful degradation. Grid connections are limited step by step until the network loading and voltages are within acceptable limits again.

The process of graceful degradation can be referred as an active power curtailment mechanism that dictates the amount of power flow at certain connection points. The DSO can differentiate among the connection points by providing different levels of reliability to various types of connections. The connection capacities can in general be distinguished by firm and non-firm capacities. The amount of power that can be curtailed through a predefined contract is termed as non-firm power capacity. In other words, the non-firm capacity can be interrupted during network emergency situations based on bilateral contracts between the prosumer and the DSO. This can be organized as an extra contract next to the conventional contract between prosumers and the suppliers. Contrary to the non-firm capacity, the firm capacity, as is the case in the conventional contract, is needed to be maintained at all times [4], [9], [11]. Unlike the conventional load-shedding methods, this type of advanced power curtailment mechanism allows the users to have a limited access to the network. Therefore, the overall network reliability is improved by avoiding the power outage in a network congestion point.

III. REAL-TIME CONGESTION MANAGEMENT

As discussed in the earlier sections, distribution transformers are more prone to the congestions than other network assets. The scope of this paper is thus focused on the congestion management of MV/LV distribution transformers.
Overloading of the MV/LV transformer might occur due to instantaneous charging of the large number of EVs or switching on simultaneously HPs. The severe situation of congestion can have an impact to the life-time of the transformer or even leading to some damages. However, the thermal dynamics involved in the loading allows the transformer to be overloaded for a certain duration of time. Therefore, the procurement of flexibility needs to be aligned with actual status and corresponding cost of overloading of the transformer.

In the following sub-section, the thermal overloading of the transformer is first explained. The integration of this physical model with the DR-based control mechanism is then presented.

A. Thermal overloading of the transformer

The insulation degradation of a transformer is a function of both temperature and time and the degradation is realized when the minimum time of overloading is 30 minutes [17], [18]. Then the instantaneous load is added with each potential load shift to determine the expected load for the next time step by the following:

\[ L_{exp}(t+1) = L(t) + L_s(t) \]

where \( L_{exp} \) is the expected load, \( L \) is the original load and \( L_s \) is the load shift.

This is converted to corresponding hottest spot temperature, \( \theta_H \) of the transformer. According to IEEE Std C57.12.00-1993, the hottest-spot temperature, which is the highest temperature of the winding at the operating condition, is the principal factor in determining the expected life of a transformer [17]. To determine this temperature, a ratio called the load multiplex, \( K \) is calculated and then used to calculate the top oil temperature rise, \( \Delta T_{TO} \) and hottest spot temperature rise, \( \Delta \theta_H \), as:

\[ K = \frac{\text{Expected load}}{\text{Rated load}} \]

\[ \Delta \theta_{T0} = \Delta \theta_{T0,R} \left[ \frac{K^2R + 1}{R + 1} \right] \]

\[ \Delta \theta_H = \Delta \theta_{H,R}K^2 \]

where \( \Delta \theta_{T0,R} \) is the top oil temperature rise at rated load, \( \Delta \theta_{H,R} \) is hottest-spot temperature at the rated load and \( R \) is the ratio of load loss at rated load to no-load loss at rated load.

The ambient temperature, \( \theta_A \) is the temperature of the air in contact with the radiators or heat exchangers averaged over 24 hours. It signifies the load carrying capability of a transformer as the temperature rises for any load is added to it to calculate the actual operating temperature. The standard ambient temperature is assumed to be 30°C [19].

Finally, \( \theta_H \) can be found by summing the ambient temperature with the above mentioned temperature rises.

\[ \theta_H = \theta_A + \Delta \theta_{T0} + \Delta \theta_H \]

Arrhenius reaction rate theory is taken as the basis to calculate Aging Acceleration Factor (\( F_{AA} \)) for the respective load and temperature. The aging of the transformer insulation is indicated by \( F_{AA} \). The value of \( F_{AA} \) is greater than 1 if \( \theta_H \) is greater than the reference temperature of 110°C and is less than 1 if \( \theta_H \) is less than 110°C [19].

\[ F_{AA} = e^{\left[ \frac{1500}{\theta_H + 273} \frac{1500}{\theta_H + 273} \right]} \]  

The equivalent aging factor, \( F_{eqv} \) is determined by taking the load history of the earlier half an hour of load. If there are \( N \) number of time intervals and the time interval is represented by \( \Delta t \) hours then \( F_{eqv} \) can be represented by eq. (7). With \( F_{eqv} \), time of overloading and normal insulation life in hours, \( T_{int} \), the per unit loss of life, \( T_{tol} \) is determined. According to IEEE standards the normal insulation life of a well dried, oxygen free distribution transformer is 180000 hours or 20.55 years. \( T_{tol} \) is therefore calculated by eq. (8).

\[ F_{eqv} = \sum_{n=1}^{N} F_{AA} \Delta t_n \]  

\[ T_{tol} = \frac{T_{eqv}}{T_{int}} \]  

B. Transformer aging cost

The aging cost, \( C_{ag} \) can be determined by multiplying the loss of life which is in per unit with the total owning cost (TOC), \( C_o \) of the transformer. The TOC method is generally regarded as one of the most cost and resource efficient method for economic analysis of a transformer [20]. TOC not only takes the initial cost into account but also the cost to operate and maintain the transformer is considered and it is calculated over the life span of a transformer. The TOC can be determined from purchase cost \( C_p \), cost of no-load loss, \( C_{NL} \) and cost of load loss \( C_{LL} \) of the transformer [20].

\[ C_o = C_p + C_{NL} + C_{LL} \]

\[ C_{ag} = T_{tol} C_o \]

If \( C_{ag} \) is found to be greater than the aging cost at nominal rating of the transformer, \( C_{ag,R} \) then the overloading cost, \( C_{OL} \) is determined by their arithmetic difference. Otherwise, the overloading cost is assumed to be zero.

\[ C_{OL} = \begin{cases} C_{ag} - C_{ag,R} & \text{when } C_{ag} > C_{ag,R} \\ 0 & \text{otherwise} \end{cases} \]

C. Integrated congestion management solution

The integrated approach for real-time congestion management is proposed combining a cost-based control of DR mechanism with the real-time thermal model of the transformer and graceful degradation. As shown in Fig. 1, the agent-based DR architecture is used for the system platform due to the inherent scalability and the ability to quantify the flexibility. A DSO service is designed in the platform to coordinate the mechanism.

The following sections discuss the detailed model of the control approaches.
2) Active power curtailment
The process of graceful degradation is characterized by active power curtailment mechanisms when the cost-based control cannot procure flexibility to resolve the congestion. This happens when the amount of load in the cluster is considerably higher compared to the local generation and vice versa. Therefore the alteration of price signals cannot influence the individual devices anymore. In order to address the congestion in such a case, the flow of power in individual connection points are limited to a lower than nominal value.

As described in [4], two types of mechanisms can be used to coordinate the process of graceful degradation based on the amount of curtailment, namely hard and soft curtailment. The hard curtailment is defined as the curtailment of all non-firm capacities in the connection points. The total curtailment in the cluster can thus be defined as the summation of the non-firm capacities of all the connection points downstream of the transformer. This can be presented as:

\[ P_{\text{curtail,hard}} = \sum_{i \in N} P_{\text{nonfirm},i} \] (12)

where \( P_{\text{nonfirm},i} \) denotes the non-firm capacity at each of the connection points. However, since the non-firm capacities at the connection points can be significantly lower than the nominal capacity, this method results in more curtailment at all the connection points than the amount needed to solve the problem.

The method of soft curtailment solves the limitation of the hard curtailment by calculating the required amount of curtailment and distributing the amount among the connection points depending on their priorities. This is achieved by introducing a curtailment coefficient, \( w_{\text{curtail},i} \) as:

\[ P_{\text{curtail,soft}} = \sum_{i \in N} w_{\text{curtail},i} P_{\text{nonfirm},i} \] (13)

![Figure 1. The integrated congestion management](image1)

1) Cost-based control
The cost-based control enables the DSO to influence the flexible devices of the prosumers to manage the congestions. When flexibility is procured by the DSO from the prosumers, it will have market consequences for the balance responsible parties (BRPs). Consequently, it necessitates a sound financial basis for any load altering action by the DSO or any market party. The developed role of DSO service is therefore primarily responsible for the market solution for acquiring and dispatching flexibility.

The process of cost-based control starts when the DSO concentrator receives all the bids from the children agents and is ready to send the aggregated bid to the parent agent. The whole process, depicted in Fig. 2, is explained as follows:

- **Step 1** - Determining overloading cost: The DSO flex service consists of a load cost calculator (LCC) that converts the thermal overloading of the transformer into a corresponding monetary cost. There are two inputs for the LCC in each time step, the instantaneous load of the transformer and the available load shifts from the flex offers. The output of the LCC is the overloading cost of the transformer obtained in (11).

- **Step 2** - Creating the flex order and transforming bid curve: In this step, \( C_{OL,i} \) is sent to the flex service and added with the respective flex prices to determine the overall cost. This is done for each of the flex offers available in the time step. After listing the total cost for each of them, the flex offer that corresponds to the minimum cost, is selected and subsequently converted into the flex order to be dispatched.

- **Step 3** - Creating flex offer: The DSO concentrator sends the aggregated bid curve to AGR-DSO interface. Upon receiving the aggregated bid curve, the AGR-DSO creates multiple flex offers with corresponding load shifts based on the received bid curve. The price from previous time step is taken as the reference; this is based on the assumption that the price variation between consecutive time steps is small. The flex offers with their corresponding load shifts are then sent to the DSO flex service.

![Figure 2. Mechanism of the integrated congestion management](image2)
The curtailment coefficient dictates the amount of curtailed active power at a connection point. For instance, if the curtailment coefficient is set as 1, the non-firm capacity is completely switched off. Because of the innate capability of the soft curtailment to cause minimal interruption for the prosumers, the scope of the method used in this paper is limited within soft curtailment methods with uniform power curtailment at the connection points.

IV. CASE STUDY

A. Description of the case study

A case study is performed with full penetration of solar PV, heat pump, EV along with uncontrolled loads in a Dutch LV residential network as illustrated in Fig. 3. A 100kVA MV/LV transformer feeds the radial LV network from the MV bus. One outgoing feeder with 20 households are considered for the simulation. Rest of the network is considered as a lumped load in the LV bus.

The simulation is performed for a typical winter day in February which is usually the coldest time of the year. The network model is built in Matlab/Simulink environment while the agent-based DR mechanism is carried out by Java agents in JADE (Java Agent Development Framework).

The uncontrolled base loads can be represented as aggregated loads of residential consumers and modeled using normalized profiles. Actual consumption from such normalized profiles of 400 households are calculated by multiplying them with 3400kWh that represents the average annual energy demand per household in Netherlands.

The behaviours of the individual flexible loads like heat pump and EV and local generation technologies like solar PVs are modeled according to the functionalities used in [21]. Detailed modeling methods of these technologies are explained in [14]. Information related to the case study are summarized in Table I.

B. Numerical results

The case is run for one day with a time step of 15 minutes. First, the loading of the transformer is observed without any congestion management measures. Next, the proposed integrated approach is implemented to observe the real-time effects on the loading of the transformer. The following sections discuss the key-findings more in detail.

1) Internal price

The aggregator in the agent-based DR platform matches the local supply and demand and calculates the internal equilibrium price for the cluster. The local price signal in the cluster is bound within per unit values of 0 and 1 which also reflects the loading status in the cluster. When the local generation exceeds the local load in the cluster the price is set at 0 p.u. Similarly the value of 1 p.u. implies the excess of load compared to local generation.

![Figure 3. 24-bus LV network model for simulation](image)

The equilibrium price for the simulation time window is illustrated in Fig. 4. The price indicates that during the early and evening hours of the day the consumption is much higher than the local generation leading to the highest value of the price. Consequently the price cannot be increased anymore to influence the consumers to lower their consumption. In other words, flexibility cannot be procured from the market anymore to deal with network congestions. Similar situations occur when the local generation exceeds the local load and the price is set at zero. In such a case the DSO cannot increase the load in the cluster by further lowering the price.

![Figure 4. Internal prices for the simulation time](image)

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1 Database for Dutch Electricity Consumption. Available at: EDSN.nl
An equilibrium point exists when the local load matches the generation in the cluster. In this case the DSO can shift the load in both directions thus procuring the available flexibility by altering the price depending on the level of thermal overloading.

2) **Loading of the transformer**

The result of the proposed congestion management mechanism on the transformer loading is presented in Fig. 5. It is observed that the congestion occurs first before 1000 hours. As seen from the internal price, there exists an equilibrium price at this time instant. Therefore, the DSO calculates the resulting overloading costs and assigns the cost to lower the load in the cluster. Therefore, the load decreases gradually before eventually relieving the congestion after 30 minutes. A similar situation occurs at 1100 hours in the morning when the congestion is resolved after 15 minutes.

However, the load in the transformer exceeds the thermal capacity again at 1800 hours for a longer time duration. The price is set at the highest value that indicates that the adequate flexibility is not available in the cluster. To solve the problem of congestion, the DSO invokes the graceful degradation mechanism and limits the load at the connection points. As the communication time interval is 15 minutes, the DSO calculates the necessary amount of curtailment and implements the measure in the next time step. This results in the successive small peaks in the loading of the transformer.

A lower value of the transformer load can be observed from Fig. 5 during 1200-1400 hours. The price values indicate that there remains excess generation in the cluster at the time period. This results in a reverse power flows from the feeder to the direction of the transformer. Therefore, the load of the transformer represents only the consumption by the rest of the network minus the flow from the feeder studied.

The loading after congestion management also reveals that, immediately after solving the congestion, the load is higher than the initial load without any control actions. This is because of the flexible devices at the household which tend to operate to maintain the comfort level of the users even if the price is high. This does not cause a significant increase in the transformer load in case of the cost-based control because the local generation is sufficient to meet the local loads. However, after the graceful degradation, the load remains considerably higher than the load without any control. This is because no flexibility is available in the cluster and the loads cannot be supplied with local generation.

3) **Effect on overloading cost**

The proposed approach is evaluated in terms of the total duration of overloading and corresponding overloading costs of the transformer. The results are summarized in Table III. Application of only graceful degradation results in the minimum duration of overloading in the whole day as the process does not involve the flexibility procured from the market.

However, this also results in higher amount of curtailed energy for the prosumers. The integrated approach tackles the problem efficiently as it not only results in a considerably lower overloading cost and duration of overloading, at the same time it also reduces the amount of curtailed energy than graceful degradation. The overloading costs with the graceful degradation and integrated approach becomes significantly lower than the cost at original loading and with cost-based control only. This is consistent with the duration of overloading as the graceful degradation and integrated approach curtails active power consumption during the times of overloading.

![Transformer loading with and without congestion management](image_url)
V. CONCLUSIONS

The focus of this paper has been to identify the possibilities of an integrated mechanism merging two approaches of congestion management, namely cost-based control and graceful degradation. The developments in the power distribution network and electricity market will lead to more uncertainties and complex interactions among the entities involved in the entire power system. The integrated approach can be a very suitable tool to solve the network congestions in such an intricate scenario. It combines the inherent benefits of a market-based solution to procure flexibilities from the small-scale prosumers with the more direct approach of graceful degradation when flexibility is not available.

The simulation results indicate the feasibility and expected outcomes of the proposed approaches. It needs to be noted that, while the cost-based control causes different pricing at different sub-clusters, the prosumers should in principle be billed based on the price set at the Aggregator level. However, if some prosumers have changed their load because of the price shift done at their local level, they need to be compensated accordingly. Therefore it is proposed that the prosumers who offered flexibility to the DSO must be administrated and the incentive paid by the DSO to the Aggregator is used to compensate for their altered behaviours.

The future research in this topic will be directed to a more sophisticated control methodology to address the attributes of the individual prosumers. This include the control of voltage level violations at the connection points, minimization of the network losses and reducing interruption by a smart curtailment approach in the graceful degradation.

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