ROLE OF MICROGRIDS IN DISTRIBUTION NETWORK CONGESTION MANAGEMENT

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ABSTRACT

In an electricity system without much renewable energy resources (RESs), there is correlation between wholesale electricity prices and demand in such a manner when electricity price rise, demand is high. But, high share of RESs can have a weakening impact on this correlation. Due to this effect, price-responsive entities like the non-utility microgrids (MGs) will react to a low wholesale market price while network load is high and simultaneously import power from the distribution system which causes to network congestion. In this context, this paper proposes a flexibility control framework of non-utility MGs for congestion management which is mapped on a bi-level model. The model states that the task of the DSO is to find the lowest Dynamic Tariff (DT) such that when the non-utility MGs aggregator minimizes his operation costs, the sum of inelastic demand and the non-utility MGs power exchange does not violate the network constraints. By using Karush–Kuhn–Tucker conditions the proposed bi-level model can be transformed to a single level optimization problem and be solved by commercial solvers.

Keywords—Congestion management, distribution networks, Dynamic tariff, non-utility MGs, RESs, merit order effect.

INTRODUCTION

In deregulated power systems, electricity prices play an important role to balance the production of renewable energy, such as wind power and solar power, and the behavior of flexible demands, such as electric vehicles (EVs), heat pumps (HPs) equipped with energy storages and microgrids. Congestion management is one of the challenges that the system operators will face with increasing penetration of renewable energy and flexible demands[1]. Besides the congestion in transmission level, it may also occur in distribution networks, especially when more and more distributed energy resources (DERs) and flexible demands are integrated at the distribution level and also under the effect of weakened correlation between wholesale electricity price and demand.
It is a great challenge to manage and operate the distribution system with high penetration of the new and flexible power sources, like MGs and EVs and HPs. The challenge includes the issue of imbalance between production and consumption, and the issue of the congestion due to simultaneous power injection and absorption of DERs. To solve (or alleviate) the under-voltage/over-voltage and overloading issues, distribution system operators (DSOs) can reinforce the distribution network (i.e. use cables/lines with higher current carrying capability and smaller impedance). The DSO can also change the total active and reactive power in system nodes by installing local new DGs and FACTS devices, such as static VAR compensators (SVCs), or by motivating the customers to change active and reactive power via market-based methods or directly controlled method under pre-agreements. Market-based methods or indirect control methods are defined as the methods that employ prices or incentives to influence the behavior of DERs such that congestion on distribution networks is alleviated. Direct control methods refer to those methods in which the DSO can directly control power system components, such as sectioning switches (network reconfiguration), On-Load Tap Changers (OLTC), SVC, grid-owned DGs and in some cases, customer owned DGs. A brief review of congestion management method can be seen in Table 1. The concentration of this paper is on Dynamic Tariff (DT) as an indirect control method for congestion management. In the literatures, significant attention has been paid toward the role of EVs as price responsive loads in congestion issues of distribution networks with high share of RESs. Although, due to the knowledge of the author there isn't any significant research work about the congestion management of future distribution networks with high penetration of microgrids, specifically non-utility microgrids which are not under the direct control of DSOs. The Department of Energy (DOE) of the US defines the microgrid as ''a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode." The behavior of these new players as the building blocks of future distribution networks should be analyzed in arising problems and challenges of the future, especially those derived from increasing penetration of RESs in the power system.

Table 1: Summery of the congestion management methods [2]

Method	Responsible parties	Time frame	Objective
Dynamic Tariff (DT)	only DSO	before spot market	lowest DT, that could prevent congestion
Distribution capacity market	DSO and aggregators	before spot market	lowest tariff, that could prevent congestion
Intra-day shadow price	DSO and aggregators, but DSO has no profit	after spot market, tens of minutes before operation	lowest imbalance
Flexibility service market	DSO and aggregators, but aggregators are not obliged	parallel to the conventional market	prevent congestion
Reconfiguration	only DSO	it can be either a day-ahead planning or a real-time operation	minimize line losses, balance line loadings, etc.
Reactive power control			minimize line losses, maximize load-ability, etc.
Active power control			minimize the adjustments, minimize the cost of adjustments, etc.

This paper proposes a flexibility control framework of non-utility MGs for congestion management of distribution networks with considering the impact of high penetration of RESs on wholesale market prices. The proposed framework is mapped on a bi-level model. The model states that the task of the DSO is to find the lowest Dynamic Tariff (DT) such that when the non-utility MGs aggregator minimizes his operation costs, the sum of inelastic demand and the non-utility MGs power exchange does not violate the network constraints.

WEAKENED CORRELATION BETWEEN WHOLESALE ELECTRICITY PRICES AND DEMAND

In an electricity system without much variable renewable energy, there is a correlation between wholesale electricity prices and demand in such a manner when electricity price rise, demand is high too. This provides an incentive for distribution level players like non-utility microgrids to purchase power during off-peak hours when electricity price is low, so it’s expected that the demand of these players should not add significantly to the peak flows through the electricity network. However, in the presence of a significant volume of wind energy this dynamic can be expected to change due to the following.

In an auction-based market mechanism, participants on the supply side place offers in the electricity market that are defined in terms of energy quantity and price. The characteristics of such offers may vary depending upon the market rules and mechanisms, but overall, the price part directly relates to a short-run marginal cost, i.e., the cost of generating an extra unit of energy. All generation offers may be seen as forming a global supply curve which serves as a basis for clearing the market. This global supply curve is built following a merit order principle: supply offers are ranked in a straightforward manner based on their short-run marginal costs. For renewable energy producers, this cost of producing an extra unit of energy is generally zero. It can actually be negative if support mechanisms rewarding on the basis of every unit of generated energy are considered [3]. Then, a consequence of a large volume of wind energy will be that the current correlation between the wholesale electricity price and network flow will become weaker and this may result in low wholesale prices despite the fact that consumption is high, and in this condition, non-utility microgrids reacting to the price could therefore cause even higher network loads. Figure 1 shows the merit order effect of RESs with zero marginal cost. It can be seen that because of prioritization of RESs other generation resources with non-zero marginal costs are shifted to right side of supply curve and meet the demand curve in a lower price in comparison with the case that RESs are not considered. It should be noted that as the penetration level of RESs increases, this impact can be more severe.

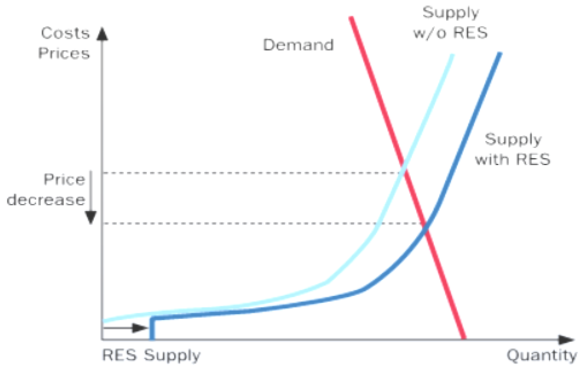

Figure 1: Merit order effect of renewable resources

FLEXIBILITY MANAGEMENT FRAMEWORK OF NON-UTILITY MGS FOR CONGESTION MANAGEMENT

Situations where electricity retailers and consumers enter into contracts at a flat price are commonplace today. Under these conditions, small consumers are totally inflexible, as they have no incentive to modify their consumption patterns to better follow the supply. In order to unlock the potential flexibility of consumers, a number of initiatives have been proposed or put in practice[3, 4]. This released flexibility which can be defined as a power adjustment with a specific size and direction, sustained at a given moment for a given duration from a specific location within the network can be used for multiple purposes, ranging from network congestion management, supply portfolio optimization and renewable integration[5].
The concept of influencing consumer preferences by a price signal is not new. Indeed, time-of-use prices have replaced fixed-price tariffs for small consumers in many countries during the last decades. In a time-of-use pricing scheme, electricity has a higher price during peak-demand hours than during off-peak hours of the day. On the contrary, consumption during the night hours is incentivized by lower prices than during diurnal hours. Time-of-use tariffs can certainly play an important role in decreasing the total system costs by influencing consumer behavior, thus moving consumption to off-peak hours. However, their relevance is challenged as the penetration of renewables into power systems grows sufficiently large to be able to influence prices in the wholesale electricity markets. Time-of-use tariffs are static, i.e., they are fixed long time in advance, and therefore unable to adapt to the rapid fluctuations of renewables. As stochastic production, in particular solar power, can lower market prices even during the peak hours of the day, the price signal must adapt dynamically on the basis of the forecast level of renewable output. Real-time dynamic pricing is meant to serve this purpose [6].
It should be noted that the vital step in order to evolve from a setup where supply follows demand to one where demand follows supply is that power systems must undergo drastic structural and operational changes. Indeed, bidirectional communication systems must be put in place to send appropriate signals to flexible consumers to exploit their flexibility nearly in real-time, and to monitor the status of the system. In turn, consumers must be equipped with "intelligent" appliances or appliance controllers, capable of optimizing consumption according to the owner's preferences and the market signals received.
With regard to aforementioned context, for defining the flexibility management framework, there are four fundamental question that should be answered:

- Who is responsible for managing this flexibility?
- What resources are managed?
- Why this flexibility is managed?
- How is flexibility activated?
- Who are the actors involved?

DSO is the responsible entity (*who*) for managing the flexibility of non-utility MGs (*what*) for congestion management (*Why*) of the network. Within this proposed framework, a time-dependent varying tariff (*How*) is presented to the non-utility MGs via communication link. This tariff stimulates the non-utility MGs to follow the network condition and alleviate the possible congestion. The time-dependent varying tariff includes both a price component of the wholesale market and the time-dependent network tariff of the DSO which is in fact the control signal for flexibility management. In the proposed framework, non-utility MGs are aggregated by a local aggregator (other actor) and participate in wholesale electricity market. Also, the aggregate demand of the MGs is assumed to be large enough to the wholesale electricity price[7]. The proposed framework is depicted in Figure 2.

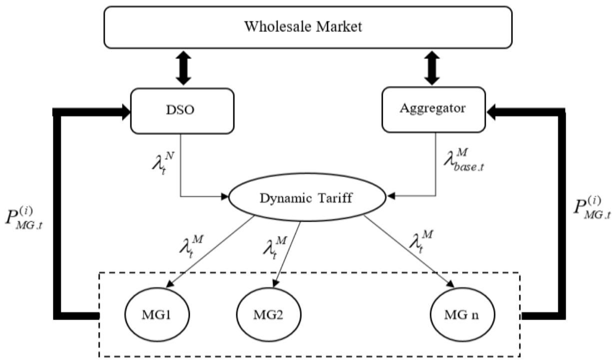

Figure 2: Proposed framework for flexibility management of non-utility MGs

MATHEMATICAL FORMULATION OF THE PROPOSED FRAMEWORK

The proposed model for congestion management of distribution network with high share of RESs in presence of non-utility microgrids as price-responsive players can be structured as a hierarchical optimization problem, comprising the following problems:

- **First level**: The optimization problem of DSO as the DT-setting entity which decides the appropriate dynamic price signal to influence the non-utility microgrids in such a way that network constraints are not violated.
- **Second level**: The non-utility MGs problems which decide on the energy management plan that maximizes their utility function once a dynamic price sequence is given.

Second Level problem

In this level, the local aggregator decides on energy management of non-utility MGs and seeks for minimization of the total operation cost. In the proposed framework, the total load of the distribution system is partitioned to the power exchanged by non-utility MGs and power consumed by other loads. We will refer to the latter as 'baseline electricity consumption', which we assume to be perfectly price-inelastic. Therefore, Demand of electricity in the distribution system is given by:

$$P_t = P_{base,t} + P_{MG,t} \tag{1}$$

Where $P_{base,t}$ is the baseline demand and $P_{MG,t}$ is the price-responsive demand of non-utility MGs. It should be noted that $P_{MG,t}$ can be positive or negative due to the interaction of non-utility MGs with the distribution system.

Also, to consider the impact of aggregated MGs power trade with wholesale market, a MGs dependent part in the electricity price is added [8]:

$$\lambda_t^M = \lambda_{base,t}^M + \beta P_{MG,t} \tag{2}$$

Where $\lambda_{base,t}^M$ is the baseline electricity price at time t and $\beta P_{MG,t}$ is the MGs dependent part and the coefficient can be estimated by sensitivity analysis of power plants merit order. If this feedback would not be taken into account, all MGs demand would be programmed in a short time interval with the lowest prices in the optimization period, causing unrealistically high peaks in demand and also technical problems.

As mentioned before, the time-dependent varying tariff or dynamic tariff comprises a price component of the wholesale market and the time-dependent network tariff λ_t^N of the DSO. Then, the second level problem takes the following form:

$$\min \sum_{i=1}^{N_{MG}} \sum_{t=1}^{N_t} \Big[F^{(i)}(X_t^{(i)}) + (\lambda_t^N + \lambda_{base,t}^M) P_{MG,t}^{(i)} + \beta P_{MG,t}^{(i)^2} \Big] \tag{3}$$

$$s.t.$$

$$g_k^{(i)}(X_t^{(i)}) \le 0 \quad k = 1,2,...,K \quad \forall i,t \tag{4}$$

$$h_m^{(i)}(X_t^{(i)}) = 0 \quad m = 1,2,...,M \quad \forall i,t \tag{5}$$

Where $X_t^{(i)}$ denotes the state variables of non-utility MG i in time t and $F^{(i)}(X_t^{(i)})$ is the operation cost of non-utility MG i dispatchable units. Constraints 4 and 5 represent the typical constraints of a microgrid energy management optimization problem that can be find in [9].

First Level Problem

In this level, the DSO as the DT-setting entity determines the appropriate DT signal to influence the non-utility microgrids in such a way that network constraints are not violated and also it should minimize the additional costs imposed to non-utility MGs compared to case when there is no DT mechanism for congestion management.

A congestion management mechanism would limit the combined load of the non-utility MGs plus the inelastic baseline load to the capacity of a certain distribution system asset, for example a feeder: The fundamental constraint of this mechanism can be modeled as below:

$$\sum_{i \in MG_f} P_{MG,t}^{(i)} + P_{t,f} \le \overline{P_f} \tag{6}$$

Where $P_{MG,t}^{(i)}$ is the exchanged power of MG i with feeder f and MG_f denotes the set of MGs connected to feeder f. The minimization of (3) in combination with constraints (4)-(5) and this extra constraint leads to the optimal (minimum) operation cost of non-utility MGs while meeting the network constraints. Indeed, the theoretically optimal network tariff would be the lowest tariff that would cause the non-utility MGs power exchange plus baseline demand to be just lower than network capacity. This can be formulated as a bi-level programming problem of the following form:

$$\min \sum_{t=1}^{N_T} \lambda_t^N \tag{7}$$

$$s.t.$$

$$\sum_{i \in MG_f} P_{MG,t}^{(i)} + P_{t,f} \le \overline{P_f} \tag{8}$$

$$\min \sum_{i=1}^{N_{MG}} \sum_{t=1}^{N_t} \Big[F^{(i)}(X_t^{(i)}) + (\lambda_t^N + \lambda_{base,t}^M) P_{MG,t}^{(i)} + \beta P_{MG,t}^{(i)^2} \Big] \tag{9}$$

$$s.t.$$

$$g_k^{(i)}(X_t^{(i)}) \le 0 \quad k = 1,2,...,K \quad \forall i,t \tag{10}$$

$$h_m^{(i)}(X_t^{(i)}) = 0 \quad m = 1,2,...,M \quad \forall i,t \tag{11}$$

The problem formulation states that the task of the DSO is to find the lowest DT such that when the non-utility MGs aggregator minimizes his operation costs, the sum of inelastic demand and the non-utility MGs power exchange does not violate the network constraints. This bi-level problem cannot be tackled directly due to the optimization problem which is presented as the constraint of first level problem. However, we can replace this constraint with the set of Karush–Kuhn–Tucker conditions, which are necessary and sufficient for optimality and finally solve a single level optimization problem.

CONCLUSION

This paper highlighted the significant impact that high share of RESs can have on weakening the correlation between wholesale electricity price and demand, known as merit order effect. Due to this effect, price-responsive entities like the non-utility MGs will react to a low wholesale market price while network load is high and import power from the distribution system which causes to network congestion. For coping with this condition, a congestion management mechanism will be necessary in order to change the non-utility MGs behavior during the period wholesale prices are low. In this context, a bi-level model is proposed based on determining a DT by the DSO to influence the non-utility MGs energy management scheme in such a way the network constraints are preserved.

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