

SYSTEM ARCHITECTURE FOR MANAGING CONGESTIONS IN DISTRIBUTION GRIDS USING FLEXIBILITY

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ABSTRACT

The increased penetration of renewable, intermittent and distributed energy resources, flexible loads and EVs in the distribution network, has arisen congestion issues at medium and low voltage level. These flexible resources, aggregated by means of the Flexibility Operator (FO), can provide flexibility services to different stakeholders. The Distribution System Operator (DSO) can take advantage of these services and use flexibility for congestion management. The present paper proposes the timeline interaction structure between the DSO and the FO to exchange information, and the Optimal Flexibility Power Flow (OFPF) algorithm to calculate the Flexibility Requests (FR) required by the DSO. This methodology is developed under the INVADE H2020 Project and applied to the Spanish pilot-site, providing these services to the DSO to avoid congestions in the MV distribution grid, activating as a flexible resource a centralized energy storage (CES) installed at a secondary substation.

NOMENCLATURE

Sets, variables, and parameters

Table 1: Sets of the FOPF mathematical formulation

K	Set of nodes of the MV distribution grid
L	Set of lines of the MV distribution grid
T	Set of time periods

Table 2: Parameters of the FOPF mathematical formulation

$C_t^{flexibilityDSO}$	Flexibility activation cost accorded between the FO and the DSO for period $t \in T$ [€/kW]
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I_l^{MAX}	Maximum allowed current at line $l \in L$
$P_{i,t}$	Total active power at node $i \in K$ in period $t \in T$ [kW]
$P_{i,t}^{gen}$	Generated active power at node $i \in K$ in period $t \in T$ [kW]
$P_{i,t}^{dem}$	Demanded active power at node $i \in K$ in period $t \in T$ [kW]
$P_{i,t}^{Flex,MAX}$	Maximum active power at node $i \in K$ in period $t \in T$ from the flexibility source [kW]
$Q_{i,t}$	Total reactive power at node $i \in K$ in period $t \in T$ [kVAR]
$Q_{i,t}^{gen}$	Generated reactive power at node $i \in K$ in period $t \in T$ [kVAR]
$Q_{i,t}^{dem}$	Demanded reactive power at node $i \in K$ in period $t \in T$ [kVAR]
$Q_{i,t}^{Flex,MAX}$	Maximum reactive power at node $i \in K$ in period $t \in T$ from the flexibility source. [kVAR]
$U_{i,t}^{MAX}$	Maximum voltage at node $i \in K$ in period $t \in T$ [kV]
$U_{i,t}^{MIN}$	Minimum voltage at node $i \in K$ in period $t \in T$ [kV]
$y_{1,i,k}$	Transversal admittance value for line $i - k$, first component [S].
$y_{2,i,k}$	Transversal admittance value for line $i - k$, second component [S]
$Z_{i,k}$	Impedance value for line $i - k$ [Ω]

Table 3: Variables of the FOPF mathematical formulation

$\varphi_{i,t}^{ACT}$	Total active power injected at node i at time t from flexibility sources [kW]
$\varphi_{i,t}^{REA}$	Total reactive power injected at node i at time t from flexibility sources [kvar]
$\zeta^{flexibility}$	Total cost for utilizing internal flexibility [€]

INTRODUCTION

The increasing number of Distributed Energy Resources (DERs) placed alongside the medium voltage (MV) and low voltage (LV) distribution networks leads to the need of flexibility services for the DSO ([1], [2]). These flexibility services could be provided by several resources, from different nature, including centralized energy storage, distributed energy storage, electric vehicles, PV panels, or Flexible Loads such as water boilers or space heaters [3]. According to CEDEC, EDSO for Smart Grids, Eurelectric, and GEODE [4], flexibility is meant to be as the modification of generation injection and/or consumption patterns both on an individual and aggregated level, to provide a service within the power system.

The aggregator gathers the flexibility from customers to provide flexibility services to different stakeholders, like energy suppliers, Balance Responsible Parties (BRP), TSO, DSO and final consumers ([1], [5]). Then, the aggregator acts as a single entity when engaging in power system markets or selling services to the system operators [6]. Under the context of smart grids and flexibility services in place, distribution system operators could benefit by activating flexibility in distribution grids ([1], [7], [8], [9]). DSOs could compensate grid congestions during high consumption or production periods, reducing their networks stress. At the same time, DSO can increase their renewable generation hosting capacity by using behind-the-meter flexibility during peak production periods.

The solution offered by the INVADE project [10] is a platform based system capable of activating flexibility during constrained periods. In [11], the local flexibility market aims to provide flexibility services to the DSO by means of aggregating prosumers' flexibility. The optimization problem is developed to minimize the aggregator operation costs. The costs are based on curtailing local generation output, charging or discharging batteries, switching off curtailable and disconnectable loads and shifting loads during specific time periods. A local flexibility market design is presented in [12], described as a market-based mechanism for aggregators. BRP and DSO are the main stakeholders of these flexibility services and they can buy flexibility from the

aggregator for different purposes.

In the INVADE H2020 Project, the Flexibility Operator (FO) is in charge of the aggregator role and also acts as an ESCO, being responsible of scheduling all flexible assets according to different objective functions and flexibility contracts. By doing this, the FO also provides services to prosumers. Here, the end-user is responsible of defining their flexibility costs for all their Flexible Devices (FDs). Then, the central platform sends the control signals to the flexible device or to another broker platform which executes these signals. The aggregated services that the FO can offer to the DSO and considered in this paper are detailed in Table 4:

Table 4: Flexibility services provided to the DSO

Flexibility customer	Flexibility services	Description (Flexibility usage)
DSO	Congestion management	Avoiding the thermal overload of system components by reducing peak loads where failure due to overloading may occur.
	Voltage / Reactive power control	Using load flexibility by increasing the load or decreasing generation is an option to avoid exceeding the voltage limits, typically, when PV systems generate significant amounts of electricity.

SPANISH DSO CASE STUDY

The INVADE Spanish pilot-site has a single CES placed at a secondary substation, and the DSO is one of the flexibility buyers. In Figure 1, the scheme of the MV network can be observed.

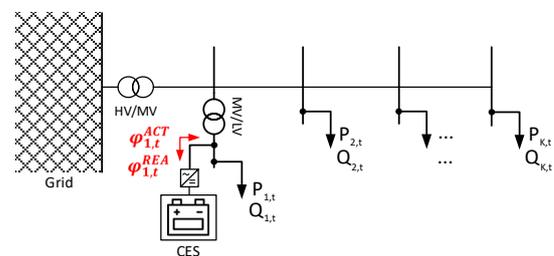


Figure 1: Pilot site grid scheme

For the DSO, the flexibility will be used to increase the distribution system hosting capacity of renewable and distributed energy. In this case, the battery will be used to provide flexibility for reducing the grid congestions and voltage problems. Additionally, the battery can improve the power quality of supply in the validation area where a

critical building is placed, and it will permit to create an electrical island and keep supplying critical loads [13].

In this pilot, three scenarios for congestion management are possible:

- Congestion management in the Secondary Substation Transformer
- Congestion management in the Primary Substation Transformer
- Congestion management along the distribution grid.

The DSO is responsible for calculating their Flexibility Requests (FR) for congestion management purposes. On the other hand, the FO is the responsible for calculating the flexibility offers, which can cover partially or entirely the DSO needs. Hence, an interaction between the DSO and the FO is needed to activate the required flexibility services. The data flow is depicted in Figure 2 below.

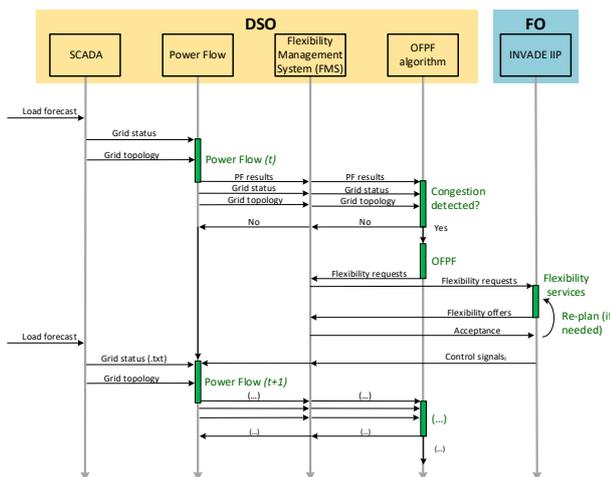


Figure 2: Flexibility requests (FRs) calculation timeline

The DSO calculates its load forecast and observes the grid status at time period $t \in T$, based on the grid topology at the same time period. Then, this information is used to calculate the Power Flow (PF). Once the calculation is done, both the Power Flow results, the grid status and the grid topology are sent to the Flexibility Management System (FMS). The FMS is the entity that works as a gateway between the DSO and the FO. This interaction and coordination is needed, since the DSO knows the grid topology and its operation, but has no information about the flexibility availability. On the other hand, the FO is aware of the flexible resources portfolio and its availability, but does not know neither the status of the distribution grid nor its congestion alongside the lines. In addition, the FMS is responsible for coordinating the calculations and the data exchange between the Power Flow and the OFFPF algorithm.

The Optimal Flexibility Power Flow algorithm (OFFPF) checks first whether there is a congestion detected in the pilot-site network. If there is a congestion in the grid, the OFFPF is calculated, to quantify the needed flexibility in the forthcoming periods. On the contrary, when no congestion is detected, the DSO continues operating the network until the PF is calculated in the next time period $t + 1 \in T$.

The FMS receives the flexibility requests (FR) from the OFFPF algorithm and delivers them to the FO, who is in charge of executing the INVADE Integrated Platform (IIP) to calculate and provide the flexibility offers to the DSO. Then, the FMS decides to accept the flexibility offers or asks for a re-plan. Once the flexibility offers are accepted, the control signals are transferred from the FO to the DSO; first to the FMS, and also to the Power Flow agent. These control signals will be included in the Power Flow calculations at time period $t + 1 \in T$. This procedure is executed repetitively throughout the grid operation horizon.

OFFPF ALGORITHM DESCRIPTION

The following section details the OFFPF algorithm, its structure, methodology, and equations. The model is developed based on a generic methodology, considering more than one flexibility source in the distribution network area. At present, only one flexibility injection point is considered in the Spanish pilot-site. However, by developing the OFFPF algorithm from a holistic perspective, the scalability of the model is guaranteed.

There is data that needs to be exchanged to calculate the flexibility requests when the PF detects a congestion in the network. There are two types of data needed for the flexibility requests calculation: static data, which should be received once; and dynamic data, which should be provided every fifteen minutes. Table 5 shows the classification of data requirements to perform the FR calculation. The identification of the nodes, lines and transformers characteristics and the physical operating limits of the network elements should be provided once, to define the pilot-site distribution network. On the contrary, the values of active power (P), reactive power (Q) and voltage at each node $i \in K$ at time period $t \in T$ are classified as dynamic data and should be provided every fifteen minutes. The demand forecast, as well as the PF results are considered dynamic data. In the case of the grid topology, it can be considered also as dynamic data with the particularity that, depending on the operation of the distribution network, it can be provided once and update the information only when there is a change in its topology.

Table 5: FOPF Data flow structure

STATIC DATA	DYNAMIC DATA (every 15 minutes)
Nodes ID Lines characteristics Transformers characteristics Operating limits of the network elements	$P_{i,t}, Q_{i,t}, U_{i,t}$ Demand forecast ($P_{i,t}^*, Q_{i,t}^*, U_{i,t}^*$) Power flow results Grid topology

DSO FLEXIBILITY REQUESTS

Optimal Flexibility Power Flow (OFPF)

The problem to solve is an AC-OPF, considering as the objective function the minimization of the total flexibility costs, but also considering the distribution network. In the following subsections the objective function is detailed, as well as all the restrictions related to the AC-OPF.

Objective function

The objective function is to minimize the total flexibility activation costs function, $\zeta^{flexibility}$. This function is based on the price for activating flexibility services, accorded between the FO and the DSO for period $t \in T$, $C_t^{flexibilityDSO}$; and the total active power injected or consumed by the flexibility resource, $\varphi_{i,t}^{ACT}$. The objective function is detailed in (1).

$$\min z = \zeta^{flexibility} = \sum_{t \in T} \left(\sum_{i \in N} C_t^{flexibilityDSO} \cdot \varphi_{i,t}^{ACT} \right) \quad (1)$$

Constraints: AC Power Flow equations

The AC power flow equations describe the power system network operating point in steady state and are based on complex phasor representation of voltage-current relationship at each node. Based on [14], the active $P_{i,t}$ and reactive $Q_{i,t}$ power flow node balance at node $i \in K$ in period $t \in T$, can be formulated.

Since the pilot-site is considering sources connected at each node of the grid, the total active power at node $i \in K$ in period $t \in T$, $P_{i,t}$, considers the active power generated, the active power demanded and the active power injected by the flexibility source Eq. (2). Regarding the reactive power, Eq. (3) also considers the reactive power generated, the reactive power consumed, and the reactive power consumed or injected by the flexibility source, being all considered at node $i \in K$ in period $t \in T$.

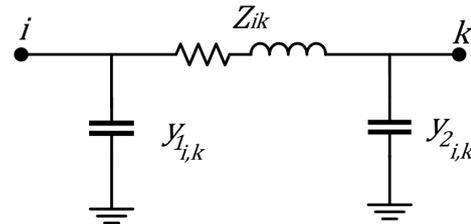
$$P_{i,t} = P_{i,t}^{gen} - P_{i,t}^{dem} + \varphi_{i,t}^{ACT} \quad (2)$$

$$Q_{i,t} = Q_{i,t}^{gen} - Q_{i,t}^{dem} + \varphi_{i,t}^{REA} \quad (3)$$

Hence, from the admittance equations, it is possible to calculate the apparent flow injected depending on the voltages at all the grid nodes.

Constraints: Line flow

The pilot-site grid is a MV distribution grid, based on underground RHZ1 cables. The line flow constraints follow the π -model of the grid since both the longitudinal impedance and the transversal capacitance of the line have to be considered. The π -model is shown in Figure 3. Each line of the distribution network is limited to the maximum allowed line current, I_l^{MAX} .


 Figure 3: π -model of the grid

Constraints: Active and Reactive by flexibility sources

The flexibility sources have both the possibility to inject or consume active power, according to up-regulation or down-regulation commands, to mitigate congestions along the distribution grid. Hence, each source is connected to a node $i \in K$, and each node will have an upper and lower active power limitation, $-P_{i,t}^{Flex,MAX}$ and $P_{i,t}^{Flex,MAX}$ in time period $t \in T$. The same occurs when dealing with reactive power. They have the possibility to inject or provide reactive power, $\varphi_{i,t}^{REA}$ to improve the quality of supply. As a result, this variable is restricted between $-Q_{i,t}^{Flex,MAX}$ and $Q_{i,t}^{Flex,MAX}$ at node $i \in K$.

The apparent power limitation S is not considered in this mathematical formulation since the active and reactive power limitations are considered as technology free. Some sources can provide $\varphi_{i,t}^{ACT}$ like PV and batteries and, other sources provide $\varphi_{i,t}^{REA}$ like EV. The DSO does not consider the technology itself and its capacity limitations, since the FO is the entity responsible for that.

Constraints: Voltage Magnitude

In the AC-OPF algorithm, the nodal voltage is restricted by an upper limit and a lower bound to guarantee the correct operation of the system. In the flexibility requests calculation algorithm, the DSO requests the flexibility services to prevent and mitigate congestions along the distribution grid, and these services can vary throughout the day. For this reason, the voltage upper and lower bounds also consider the time period $t \in T$, resulting in the following parameters, $U_{i,t}^{MIN}$ and $U_{i,t}^{MAX}$. These parameters will be provided by the DSO based on the level of risk they want to assume on congestions along the network.

CONCLUSIVE REMARKS

The present work detailed the interaction scheme between the DSO and the FO to provide flexibility services for congestion management in the MV distribution network. Both the algorithm and the equations of the OFPF are detailed to calculate the FR when a congestion is detected. The FO is then responsible for managing the FR received, prioritize them and activate the flexible resources according to the OFPF results and the interaction with the DSO.

These equations are implemented in the specific case study of the Spanish pilot-site allowing the viability test of the FR calculation and also to develop the interaction between the power system agents in the smart grid era.

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