Probabilistic assessment of congestions in LV distribution grid due to frequency regulation

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***Abstract*—This paper presents a methodology for assessing the congestion probability on a low-voltage (LV) distribution grid caused by LV residential assets providing frequency ancillary services combined with decentralized energy resources, like residential photovoltaic panels (PV). End-user profiles consider three probabilistic components: LV assets providing frequency ancillary services, baseload profiles and PV generation. Both frequency containment reserve (FCR) and automatic frequency restoration reserve (aFRR) are considered. This paper demonstrates the added value of using an Auto-Regressive Moving Average (ARMA) model to forecast frequency ancillary services compared to a simple normal distribution. It further highlights the application of FCR models for both *constant* and *instantaneous* congestion, which prevents overestimating FCR-induced LV congestion. Additionally, this paper shows that allowing aggregators to activate LV assets for aFRR using a portfolio-based approach leads to higher LV congestion than a limited-reservoir approach.**

***Index Terms*—LV congestion, frequency ancillary services, FCR, aFRR.**

I. Introduction

COUNTRIES all around the world, and in particular European countries, aim to achieve ambitious climate goals and to reduce CO2 emissions, by increasing renewable energy production and increasing loads electrification. This ongoing energy transition is strongly impacting the Low-Voltage (LV) distribution grid (< 1kV), as end users are increasingly installing distributed energy resources (e.g. photovoltaic panels (PV)), energy storage systems (e.g. residential batteries) or electric loads (e.g. electric vehicles (EV) for mobility, heat pumps (HP) for heating). These distributed energy resources are more and more encouraged to provide flexibility services, such as frequency regulation (or frequency ancillary services). For instance, in the European regulatory framework, Transmission System Operators (TSOs) are encouraged to rely on flexible assets connected to distribution grids to balance the system [1]. Nevertheless, activating or deactivating flexible LV assets to provide frequency ancillary services can lead to the violation of operational limits (e.g., voltages and currents) at the distribution level, increasing congestion risks for Distribution System Operators (DSOs).

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In that context, it is of paramount importance for DSOs to be able to assess the risk of congestion due to assets participating to frequency regulation in the presence of distributed energy resources, in order to plan and/or to operate the system such that the violation of operational limits can be avoided.

The quantification of the risk of congestion requires first an identification of the relevant operational limits that must be respected. At the level of distribution systems, two types of electrical variables must be maintained between specific limits: voltages at the various busses and currents on distribution elements (lines, transformers). Due to thermal inertia, currents do not have to be at any time to be below the branch rating. However, they have to be below the rating on a 15-min basis. Similarly, according to the EN 50160 standard, average 10 minutes rms values should be between -10% and +10% of the nominal voltage for 95% of week. But, contrarily to current limits, voltages must be also between specific limits at all times, *instantaneously*, i.e. for a 10-seconds granularity. For instance, in Belgium, generating units connected to distribution grids (e.g., PV) must be disconnected as soon as the voltage exceeds by 15% its nominal value. Consequently, the quantification of the risk of congestion requires to estimate average values of currents and voltages over 15 minutes, but also *instantaneous* values of voltages within these time periods.

Several methods have been proposed to assess the risk of congestion in LV distribution grids due to LV assets. For instance, [2] and [3] assess the impact on a LV distribution grid of LV assets such as EV, HP and PV, and [4] studies the impact of HP and PV on a Belgian LV feeder. Furthermore, [5] analyses the impact of LV assets (batteries, PV, EVs) on a real Norway grid for market-oriented activities, such as P2P and local markets. However, to the best of the authors' knowledge, only a very limited number of works consider LV assets providing frequency ancillary services and their impact caused on the LV distribution grid. Ref. [6] studies the congestion of a European LV network caused by batteries providing self-consumption combined with other activities, such as frequency reserves. Nevertheless, this works deal only with average values of currents and voltages over *constant* congestion period (i.e. 15 minutes), and none of them deal with *instantaneous* values of voltages within these time periods (i.e. 10-seconds). It is thus inadequate to estimate the risk of congestion due to frequency regulation. In North America, the transient response of LV aggregate loads providing frequency regulation is investigated in [7]. The study focuses on the surge currents due to building Heating Ventilation and Air-Conditioning (HVAC) loads when they are asked to increase their consumption (inrush/starting currents of induction motors). These surge currents, lasting typically a few hundreds of milliseconds, can have severe adverse effect on protection systems (unwanted trips). Although that work deals with instantaneous values of electrical quantities, it focuses on a problem very specific to induction motors and the approach cannot be transposed to the risk of congestion for all assets providing frequency ancillary services. There is thus a gap in the literature to assess the risk of congestion in distribution grids due to frequency regulation.

Consequently, this paper addresses this gap by proposing a novel approach to estimate average values of currents and voltages over 15 minutes, but also values of voltages with a higher granularity within these time periods, and by demonstrating its effectiveness on a case study. More specifically, the methodology will build on a Probabilistic Power Flow (PPF) [8]–[10] solved using Monte Carlo (MC) simulation. Three sources of uncertainty will be considered: LV assets profiles providing frequency ancillary services, non-flexible end-users profiles and photovoltaic production profiles. This PPF will lead to average values of currents and voltages over 15 minutes. The main original contribution of this paper consists in complementing this PPF with an Auto-Regressive Moving Average (ARMA) model predicting frequency at higher granularity (10 seconds) to estimate also value of voltages at that high granularity within period of 15 minutes.

The remainder of the paper is organized as follows. Section II presents the PPF methodology, with emphasis on the stochastic model to capture the uncertainty of LV assets providing frequency ancillary services (i.e. the ARMA model). Section III describes the case study considered and presents and discuss associated results. Finally, Section IV highlights the main conclusions of this paper.

II. Methodology

The PPF methodology, based on [8] and [11] and depicted in fig. 1, is employed to analyze the congestion probability of LV distribution grid caused by LV assets providing frequency ancillary services. The process begins with generating N stochastic profiles assigned to each customer based on the load profiles, for 15-minute intervals over a day (96 timesteps). Stochastic profiles and grid data are used as inputs to compute N deterministic power flow (PF) across 96 time steps. PF results are then evaluated against congestion thresholds.

The methodology is divided into three subsections (Profiles Calculation, Power Flow calculation and Congestion Analysis), with particular emphasis on the profiles calculation of LV assets providing frequency regulation for both context, *constant* (15-minute) and *instantaneous* (10-second resolutions), as these represent the key highlights of this work. More complex non-flexible and PV load profiles are available in the literature; however, their implementation falls outside the scope of this paper, which primarily focuses on modeling flexible load profiles that provide frequency ancillary services. The grid data will then be further detailed in the case study.

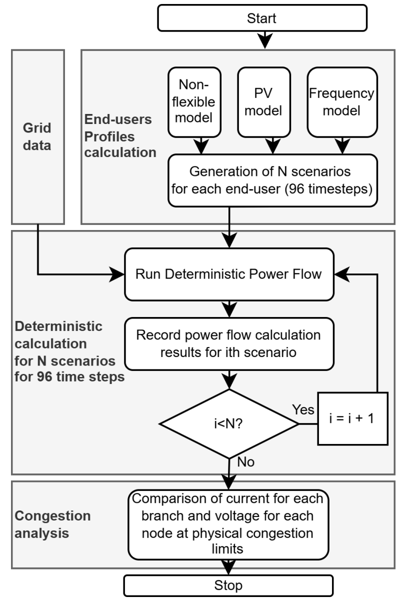

Fig. 1. Flow chart of the PPF used in this paper

A. Profiles calculation

As illustrated in fig. 1, stochastic load profiles assigned to each end-user are built on three components: a stochastic model for LV assets providing frequency regulation that will be particularly deepened in this subsection, a stochastic model for non-flexible load and a stochastic model for PV production. The term load, load profile or profile refer to both consumption and production, modeled as constant complex power given by eq. (1) for each timestep t and for each scenario N.

$$S_b^t = S_{flex,b}^t + S_{nonflex,b}^t + S_{pv,b}^t \tag{1}$$

This paper focuses on frequency ancillary services, specifically primary reserve due to its rapid and automatic activation, and secondary reserve due to its slightly slower but still fast activation and larger volume requirements. These reserves are defined as Frequency Containment Reserve (FCR) and automatic Frequency Restoration Reserve (aFRR), as applied for Continental Europe [1]. The focus on FCR and aFRR is particularly relevant since they are the first reserves accessible to LV assets in Europe. Fo example: since 2024, LV assets in Belgium are eligible for both FCR and aFRR services, comprising 10% of the assets pre-qualified for FCR [12]. Other frequency reserves, such as Replacement Reserve (RR) or faster reserves like the fast frequency reserve used in Nordic countries, are not considered in this study.

1) Flexible profile - Constant FCR: LV load profiles providing FCR are modeled as proportional to the global system frequency deviation Δf^t, as defined in eq. (2). In this context,

$P_{max,b}$ represents the maximum power reserved by each end-user for FCR. The frequency deviation Δf^t is calculated using 10-second frequency values f^t, which are randomly sampled from an ARMA model entertained on 10-seconds historical data available on Elia's opendata platform [13]. The ARMA method is chosen because it is a relevant technique to forecast signal based on time series with a high self-correlation, which is the case for global power system frequency [14], [15].

To model *constant* FCR, values are averaged over each 15-minute time step into f^t_{avg} to compute Δf^t. The computation, detailed in eq. (3), accounts for a maximum frequency deviation f_{max} of ±200 mHz, a deadband Δf_{db} of 10 mHz, and a nominal frequency f_{nom} of 50 Hz. It is important to note that Δf^t is uniform across all end-users at each time step, while $P_{max,b}$ varies between individual end-users.

$$S^t_{flex,b} = P_{max,b} \Delta f^t \tag{2}$$

$$\Delta f^t = \begin{cases} \frac{f_{nom} - f^t_{avg}}{\Delta f_{max}} & \text{if } \Delta f_{db} < |f^t_{avg} - f_{nom}| < \Delta f_{max} \\ 1 & \text{if } (f_{nom} - f^t_{avg}) \geq \Delta f_{max} \\ -1 & \text{if } (f_{nom} - f^t_{avg}) \leq \Delta f_{max} \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

2) Flexible profile - instantaneous FCR: The previous paragraph supports the use of averaged frequency data to study impact of FCR on LV distribution congestion for normal context. In contrast, this paragraph highlights the need to consider worst-case data to assess *instantaneous* frequency deviations impact on the congestion, where LV asset are modeled as $S^t_{fcr,b} = P_{max,b}$.

Indeed, in the case of unexpected extreme events, extreme frequency deviations, i.e. frequency deviation reaching the maximum limit f_{max}, occurring over few single 10-second time steps, can lead to extreme load profiles activated coincidentally and potentially causing instantaneous LV network congestion. Since frequency deviations are currently averaged over 15 minutes in the *constant* model, the worst-case scenario, and its corresponding worst-case load profile, is not fully captured in the averaged data. Three factors, i.e. automatic activation, magnitude of volumes involved, and activation coincidences, stresses the need to further investigate into the impact of instantaneous frequency deviations on the LV distribution grid. While such events are inherently unpredictable, the evolution of the frequency signal after the event can still be anticipated. Evaluating this impact includes assessing the transmission grid's ability to contain and restore frequency following extreme events and determining whether DSOs should account for such deviations in both *constant* and *instantaneous* congestion.

3) Flexible profile - aFRR profile: For the aFRR, several papers study the design strategy of aggregators to optimally define their bids for the auction mechanism [16], [17]. However, DSOs are not expected to know the specific design strategies of aggregators owning flexible assets located on their local grid.

In this context, this paper does not consider the aggregators' own design strategy but focuses on the possible impact of the LV assets providing aFRR if dispatched by TSO and fully activated by the aggregator. When the LV assets provide aFRR, LV assets are considered to provide full power activation for each product (positive or negative) starting at t_{start} and ending at t_{end} as represented in eq. (4). Hence, maximum deterministic power profile is considered when LV asset provide aFRR for a specific product.

$$S^t_{flex,b} = \begin{cases} \pm P^T_{afrrmax,b} & \text{for T in } [t_{start}, t_{end}] \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

In Belgium, flexible assets with a limited reservoir providing aFRR must ensure full activation of contracted power over a 4-hour period [18]. Two approaches are analyzed: (1) the limited reservoir approach, where maximum power is constrained by each asset's available energy, and (2) the portfolio approach, where full power is modeled as activated. These approaches are evaluated in the case studies to assess aFRR's impact on the LV distribution grid.

4) Non-flexible profile: For stochastic non-flexible load profiles, a unique load profile $S^t_{nonflex,b}$ is generated for each customer across all 96 timesteps t of the day for each of the N scenarios. The non-flexible load profile for each end-user and each time step is given by eq. (5) where $E_{year,b}$ is the yearly consumption of each end-user. $S^t_{slp,b}$ is generated by randomly sampling from a normal distribution $\mathcal{N}(SLP_t, \frac{SLP_t}{2}^2)$. The standard deviation is set to half of the mean active power.

$$S^t_{nonflex,b} = S^t_{slp,b} \cdot E_{year,b} \tag{5}$$

5) PV profile: PV production profiles are given by equation (6). The capacities of the solar panels, $P_{panels,b}$, and inverters, $P_{inv,b}$, are assumed to be known. For each scenario, a single irradiation profile, I^t, is randomly generated for all PV panels across the 96 time steps. This irradiation profile is derived from historical solar irradiation data collected over the past six years. The efficiency coefficient, η_{eff}, is used to convert the irradiation into energy production, expressed in $\frac{kWh}{kW}$ per time period.

$$S^t_{pv,b} = I^t \cdot \eta_{eff} \cdot \min(P_{panels,b}, P_{inv,b}) \tag{6}$$

B. Power flow calculation

The implemented power flow is an unbalanced three-phase PF (UTPF) using the Backward-Forward Sweep (BFS) method, as described in [19], [20]. This approach initializes with known voltage values while assuming zero branch currents and power losses. The backward sweep starts at the last bus and calculates branch currents using Eq. (7), progressing toward the transformer. Contributions from child branches and end-user loads, computed using Eq. (8), are added to the parent branches, where n, b, and k represent the branch, the child bus connected to that branch, and the iteration, respectively.

$$I_n^{k+1,t} = I_b^{k+1,t} + I_{n+1}^{k+1,t} \tag{7}$$

$$I_b^{k+1,t} = \left(\frac{S_b^t}{V_b^{k,t}}\right)^* \tag{8}$$

The forward sweep propagates voltages from the transformer, updating the voltage at each child buses based on the parent branch current and impedance as given by eq. (9). For the series impedance matrix Z_{red}, the reduced model capturing neutral effect specific to European LV feeders is used [21].

$$V_b^{k+1,t} = V_{b-1}^{k+1,t} + Z_{red,n} I_n^{k+1,t} \tag{9}$$

The process repeats until voltage mismatches at all buses fall below a specified tolerance as given by eq. (10).

$$\frac{||V_b^{k+1,t}| - |V_b^{k,t}||}{V_{nom}} \leq tolerance \tag{10}$$

This BFS UTPF is computed repeatedly for each time step for each N scenarios.

C. Congestion analysis

Voltage and current levels across the entire feeder are evaluated against predefined thresholds based on the EN 50160 standard or DSOs practices. Undervoltage (UV) congestion is defined when the voltage drops below 0.9 p.u. over a continuous 15-minute period or below 0.85 p.u. during *instantaneous* variations. Overvoltage (OV) congestion occurs when the voltage exceeds 1.1 p.u. over a continuous 15-minute period or 1.15 p.u. during *instantaneous* variations. Overcurrent (OC) congestion is defined as the current exceeding the branch's ampacity for more than 15 minutes. It is important to distinguish that *constant* thresholds apply to 15-minute averaged values, while *instantaneous* thresholds correspond to 10-second intervals, which still both represent steady-state grid operation rather than transient conditions.

III. Case Study

A. Description

This subsection describes the case studies considered: first the grid data and then the assumptions regarding load profiles.

Regarding grid data, the reduced IEEE European LV Test-feeder is chosen for the benchmark grid case study [22]. This grid is represented in fig. 2 with 55 end-users and their initial phase connections. Each end-user is connected to the grid with a maximum power capacity (in this case: ± 9.2 kVA). Voltage at slack bus is set at 1.05 p.u.

Regarding load profiles, half of the end-users are assumed to own LV assets providing flexibility, as well as solar panels. These assets are distributed such that one out of every two end-users is equipped.

Each end-user with flexible LV assets is assumed to contribute up to 10 kW/20 kWh for FCR or aFRR services.

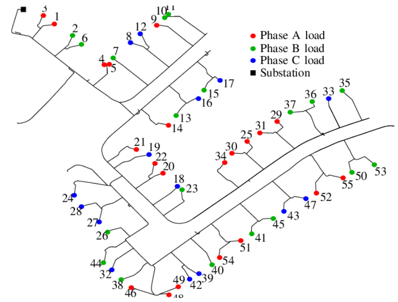

Fig. 2. Case study with IEEE European LV

Consequently, $P_{max,b}$ for FCR is set at 10 kW per end-user with flexible assets. For aFRR, two approaches are analyzed: (1) the limited reservoir approach where the maximum power is constrained by the energy capacity of 20 kWh, limiting $P_{afrrmax,b}$ to 5 kW, and (2) the portfolio approach where residential batteries can deliver maximum power regardless of their individual energy capacity, setting $P_{afrrmax,b}$ to 10 kW. The case study examines the aFRR P4 product, where LV assets inject power into the grid from 12:00 to 16:00 when activated.

Non-flexible load profiles and PV production profiles are derived from historical data, as described in the methodology. The mean SLP_t for non-flexible load profile is derived from the 2023 Belgian synthetic load profiles, as published by the system operator federation in [23]. Yearly energy is set to 3500kWh. The summer solstice is selected as the reference day for sampling, ensuring adequate solar irradiance for PV production. Each PV system is configured with an inverter capacity of 5 kVA and a peak installed power of 5 kWp.

B. Numerical results - Instantaneous FCR model validation

This subsection outlines the rationale for adapting FCR load profiles for *constant* and *instantaneous* congestion thresholds.

In this paper, frequency deviation is computed with an ARMA model. It is again employed to predict frequency behavior following an unexpected extreme event. The model's performance is validated against historical frequency data from January 8, 2021, when the frequency dropped to 49.8 Hz and benchmarked against a naive persistent model.

Figure 3 illustrates the frequency behavior post-drop, comparing historical data (blue and green) with the ARMA probabilistic prediction (average in orange, 99.9% prediction interval in light orange) and the naive persistent model (purple). Blue data are used to entertain ARMA model and green to data to validate it. Over a 15-minute period, ARMA achieves a lower mean squared error (MSE) of 0.23966 compared to 0.29558 for the naive model, confirming ARMA's superior predictive accuracy at a 10-second granularity, after the occurence of an extreme frequency event.

The predicted average frequency returns to the historical frequency within 6 minutes 10 seconds. This finding is critical, as OC must last longer than 15 minutes to damage network components like cables or transformers due to their thermal

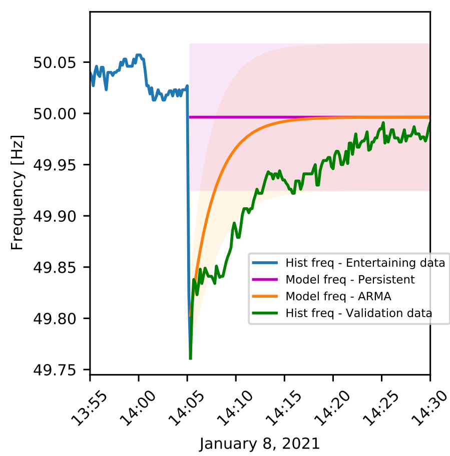

Fig. 3. Part of historic entertaining frequency data at 10 seconds granularity till January 8, 2021, at 14:05:20 in blue, forecast frequency data with ARMA model in orange and with persistant model in purple, historic frequency data to validate from January 8, 2021 at 14:05:20 in green

inertia. Furthermore, OV and UV thresholds are defined differently for *constant* and *instantaneous* voltage variations. These results validate the use of 15-minute averaged frequency data for assessing *constant* congestion thresholds, as frequency is restored well within the averaging period. However, for instantaneous congestion thresholds, relying solely on 15-minute averages may overlook instantaneous frequency peaks and FCR model is suggested to be adapted in the form $S^t_{fcr,b} = P_{max,b}$.

C. Numerical results - Impact of LV assets providing FCR

Fig. 4 shows the probability distribution of voltages [p.u.] per phase for the most loaded bus (bus 80 connecting end-user 36) on the summer solstice. The left panel represents the scenario where LV assets providing FCR follow an averaged probabilistic frequency signal for the 15-minutes analysis. In this case, voltages remain below the *constant* OV congestion threshold (red dotted line), indicating no congestion.

The right panel depicts the voltages per phase for the instantaneous analysis. In this scenario, LV assets are modeled to deliver maximum power as a response to an unexpected extreme frequency event. Consequently to consider instantaneous congestion, the OV congestion threshold is raised to 1.15 p.u. The figure shows that while voltages may momentarily exceed the *constant* congestion threshold during the extreme event (light dotted line), they remain below the instantaneous congestion threshold (red dotted line). As a result, no *instantaneous* congestion occurs in this scenario.

Therefore, this result highlights the importance of using consistent congestion thresholds to avoid overestimating the congestion caused by FCR on the LV distribution grid. This approach helps increase the access of LV flexibility for frequency ancillary services.

D. Numerical results - Impact of LV assets providing aFRR

Congestion is absent in the limited reservoir approach but exceeds 0% in the portfolio approach, with OV and OC probabilities arising from P4 activation between 12:00 and 16:00. Congestion caused by limited reservoir approach for this case study is therefore not represented.

Fig. 5 shows the congestion probability distribution for branch 0 on the summer solstice when the LV assets are providing aFRR for the P4 product. The left figure presents the current probability distribution per phase and per time step at branch 0. The right figure displays the two congestion probability, OV and OC, occurring on the LV distribution grid. The figure clearly shows a step increase in current yielded between 12:00 and 16:00 corresponding to the modeling of the activation of LV assets providing aFRR P4.

This raises important considerations for discussions between DSOs and TSOs regarding activation approaches for LV assets in aFRR. While LV assets offer significant potential for frequency reserve participation, their activation must be carefully managed to prevent congestion on the LV network. In this case study, the limited reservoir approach results in no congestion on the LV distribution grid, whereas the portfolio approach leads to OV and OC congestion.

IV. Conclusion

In conclusion, this paper presents a methodology to model the congestion caused by LV assets on the LV network when providing FCR and aFRR services. The impact of FCR is analyzed for both a *constant* case, with 15-minute granularity, and an *instantaneous* case.

Three key results are highlighted:

- A probabilistic ARMA model for frequency ancillary services more accurately predicts the output power of LV assets providing FCR following an extreme frequency event compared to a simple normal distribution.
- This model demonstrates that average frequency data can be applied to study impact of *constant* congestion thresholds, while extreme frequency events should only be used with *instantaneous* congestion thresholds to prevent overestimating FCR-induced LV congestion.
- Allowing aggregators to activate LV assets for aFRR using a portfolio-based approach results in greater LV congestion compared to a limited-reservoir approach.

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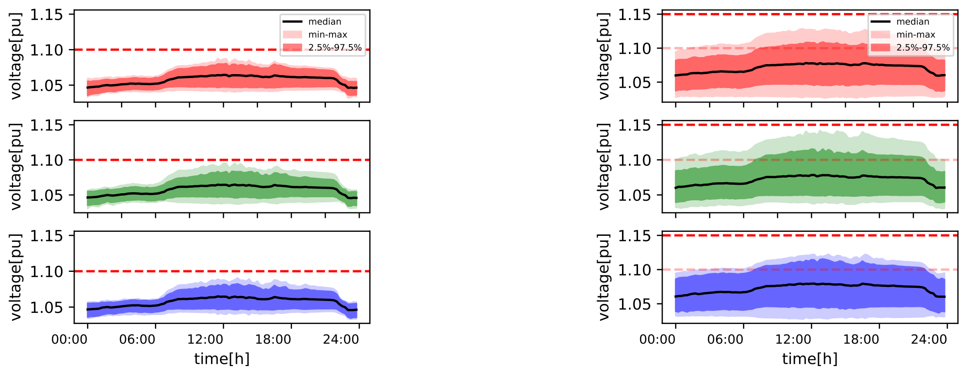
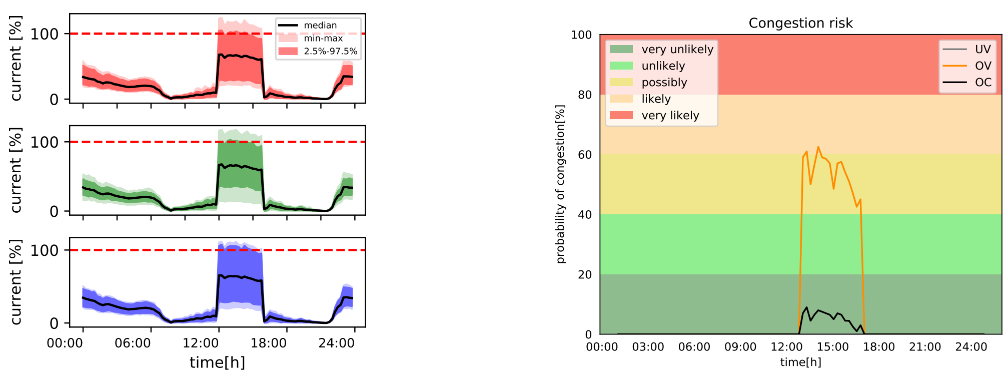


(a) LV assets following probabilistic frequency signal for constant congestion threshold

(b) LV assets following worst case frequency signal for instantaneous congestion threshold

Fig. 4. Case study I - LV assets providing FCR



(a) Current probability along the day per phase on branch 0

(b) Congestion probability along the day for the full feeder

Fig. 5. Case study II - LV assets providing aFRR P4 in a portfolio approach

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