edgeFLEX

D2.5

Inertial Response Control Concept for VPPs in Large Scale Deployment

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Abstract
This document presents the inertial control allocation algorithm developed in work package WP2 as a scheduling tool for system operators and VPPs to allocate frequency response. The report discusses the two-level optimization problem formulation and the different test use cases used for validation at a proof-of-concept level.

Keyword list
Low Inertia Power Systems, Inertia Allocation, Damping Allocation, VPP, TSO, Optimization, Frequency Support.

Disclaimer
All information provided reflects the status of the edgeFLEX project at the time of writing and may be subject to change.

Executive Summary

In this deliverable, we present the work of task T2.5 on the development of an *allocation* framework for inertial response control for large-scale VPP deployment, within the wider context of the work of WP2 of edgeFLEX. WP2 focuses on developing frequency control and inertial response related estimation and control concepts for dynamically controlled Virtual Power Plant (VPP) solutions. The main objectives of WP2 are as follows:

- Defining the scenarios and use cases for frequency and inertial response control related concepts of VPPs and low inertia power systems.
- Proposing new concepts for frequency control in current VPPs as well as for Energy Communities in future VPPs.
- Proposing new concepts to *estimate* the inertia in low inertia power systems.
- Proposing new *allocation* framework for inertial response control for large-scale VPP deployment.

The increased penetration level of Distributed Energy Resources (DERs) significantly changes the requirements and the technical and economic options available to provide frequency support ancillary services to guarantee a secure and stable operation of future power grids. Mature and sufficient technical solutions for DERs to provide ancillary services are already available. However, the cost for providing ancillary services must be economically viable for both the System Operators (SOs) and the operators of DERs. Moreover, physical constraints of generation systems and controllability must be taken into account. Hence, optimization frameworks for providing economically and technically optimized solutions are required.

In task T2.5 we develop an inertial control and damping allocation method that can be used by system operators and VPPs for frequency support scheduling, in order to meet the security requirements on short-term post-fault dynamics. This deliverable describes the developed allocation algorithm and presents the validation results considering different case studies and scenarios. Based on the validation results, we deduce the following conclusions:

- Sizing, tuning and spatial allocation of virtual inertia and damping is important.
- The inertial control allocation algorithm successfully improves the overall system dynamics and ensures the grid resilience post-fault stability while fulfilling the system predefined security constraints.
- The optimization framework facilitates efficient allocation of frequency support from DERs and conventional generation.

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1. Introduction

In the context of foreseen future low-inertia power systems, the objective of WP2 is to develop frequency control and inertial response related estimation and control concepts. The focus of the work of Task 2.5 is to develop inertial control allocation algorithms, which can be used by SOs and VPPs as planning tools for allocating frequency support ancillary services, i.e., virtual inertia and fast frequency regulation, from DERs in addition to the primary frequency control reserves, in power systems with high penetration of DERs. The objective of the developed allocation algorithms are to minimize the cost of providing frequency support ancillary services, while satisfying the constraints at system-level and device-level i.e. single generation unit constraints.

1.1 Objective of the Report

The aim of this deliverable is to describe the inertial control allocation algorithm developed within the second year of the project and provide preliminary validation results.

1.2 Outline of the Report

The report consists of four main parts. The second chapter presents an overview of inertial control allocation methods. The third chapter recalls the theory behind the power system frequency dynamics model and its relation to the overall system frequency performance metrics. The inertial control allocation algorithm developed within Task 2.5 and the validation results are described in Chapter Four. Finally, the detailed scenario and use case description is provided in the annex.

1.3 How to Read this Document

This report can be read as a standalone document. However, the interested reader can refer to the following deliverables to get a better overview of the terminology and use cases of the edgeFLEX project.

- D1.1 - Scenario description for dynamic-phasor driven voltage control for VPPs (M12) [1]: This deliverable provides an overview of the state of the art in terms of VPPs and introduces to the reader the terminology adopted within the project.
- D2.1 - Scenario description for frequency and inertial response control for VPPs (M12) [2]: in this deliverable the scenarios and the relevant use cases of the frequency and inertial response control and estimation concepts of WP2 are defined.

2. Allocation of Inertial Control

The emerging issue of low-inertia power systems, due to increasing penetration of converter-interfaced generation, is challenging for the operation and control of power systems. In such power systems, stability margins is decreasing and the system frequency dynamic response deteriorates following a disturbance. Depending on the location and current production levels of Distributed Energy Resources (DERs), the total system inertia decreases and becomes also time-variant and heterogeneously distributed. These conditions can lead to destabilizing effects, as experienced in recent real-world incidents such as the blackout in Australia in 2016 [3].

To overcome these implications of low-inertia power systems, many novel converter control strategies that provide virtual inertia and fast frequency regulation have been proposed in literature. Such strategies require energy storage (e.g., batteries) on the DC side of the converter, acting as an energy buffer, and a proper control scheme that offers inertia and /or damping as design parameters. Some of these strategies are commercially available and recommended by grid codes as ancillary services [4] [5].

However, an open question remains; where and how much inertia and damping need to be placed in different parts of the system, ahead of real-time operation, in order to ensure the grid resilience and post-fault stability?

As aforementioned, the system robustness does not only depend on the total amount of virtual inertia and damping available but also depends on the specific implementation and location of devices providing these ancillary services. This calls for the development of virtual inertia and damping allocation methods that can be used by system operators, both in planning of future power systems and in day-ahead inertia scheduling, in order to fulfill the security requirements on short-term post-fault dynamics.

The proposed approaches in literature are mainly intended for system operators and can be divided into two groups: 1) based on eigen-value sensitivity as in [6] and 2) based on minimization of system norms [7]. The drawback of the norm-based approaches is that the system norms cannot be directly related to the operational criteria defined by the system operators. The eigen-value sensitivity-based methods aim at maximizing the most critical damping ratio with explicit performance metrics constraints.

In our work, we propose a two-level model-based optimization framework to facilitate efficient allocation of frequency support ancillary services, i.e., virtual inertia and fast frequency regulation, from VPPs in addition to the primary frequency control reserves. Utilizing eigen-values' sensitivity, the optimal values of virtual inertia and damping are determined using sequential linear programming. The objective of the first level of optimization is for the TSO to minimize the total control effort of providing frequency support ancillary services, while satisfying system level constraints and physical device level constraints. At the system level, we formulate inertia and damping-dependent constraints with different timescales. Firstly, this achieves adequate damping of oscillations and secondly, ensures fulfilling the grid codes with respect to the time-domain performance objectives of frequency control. These include the rate of change of frequency, frequency nadir and quasi-steady state frequency deviation. Moreover, the considered local constraints ensure the feasibility of providing different ancillary services.
The second level of optimization is meant for the VPP operator to allocate the requested inertia and damping from the TSO to its resources. The objective of the optimization is to minimize the ancillary services provision cost for VPPs.

The proposed optimization algorithm is evaluated on the New England IEEE 39-bus benchmark system [8]. In the context of the rapid increase distributed energy resources penetration, the IEEE 39-bus system is modified to represent a future scenario of a power system with VPPs providing frequency control. The modified system includes an aggregation of DERs that provide controllable virtual inertia and damping to be allocated by the proposed inertial control allocation algorithm i.e. inertia allocation algorithm. For simplicity, we use the term *inertia allocation* in the rest of the document.

3. Frequency Dynamics Model

In this chapter, we introduce the basic dynamic frequency model for power systems which constitutes the reference model for deriving the system frequency performance constraints. The frequency dynamics in large power systems are governed by the electromechanical dynamics of synchronous generators and power converters providing frequency support.

In the following sections and subsections, the dynamics of synchronous generators and power converters are recalled and their relation to the power system frequency is established.

3.1 Dynamics of Synchronous Generators

To understand the dynamic behaviour of Synchronous Generators (SGs), let us consider an active power imbalance in the system that would disturb the equilibrium state of the generator. Like any physical moving object, the SG will show a resistance to the change in its motional state, in other words the SG will exhibit an intrinsic inertial response. Therefore, if the load increases, the rotating masses of the SG will decelerate and release Kinetic energy to counteract the power imbalance and vice versa if the load decreases, the rotating masses will accelerate and absorb the excessive energy. This rotating masses' speed is tightly linked to the system frequency, hence any power imbalance results in variations in the system frequency.

The electromechanical dynamics of SGs can be expressed in terms of the classical nonlinear Swing Equation (SE), which relates the rotating masses angular speed ω to the power imbalance ΔP, as:

$$M\frac{d\omega(t)}{dt} = \Delta P \qquad \Delta P(t) = P_m - P_e(t) \tag{1}$$

Three quantities basically define the dynamic behaviour of SGs when an equilibrium state has been breached:

1) the *mechanical power* P_m i.e. the SG set-point.
2) the *electric power* P_e fed into electric grid, i.e. the generator output power.
3) the kinetic energy stored in the rotating masses of the generators, which is related to the moment of *inertia M* of the generators.

When the system is in equilibrium state, i.e. the generation meets the load demand, the power imbalance $\Delta P = 0$, the angular speed $\omega = 2\pi f$ and the system frequency f are equal to their nominal values.

However, following any disturbance, the frequency will change. The larger the moment of inertia M, the slower the Rate of Change of Frequency (RoCoF).

Note that no control equipment is considered so far in order to understand the principal dynamic behaviour.

Frequency control structures are needed to maintain a constant system frequency. In the subsequent section we present the Primary Frequency Control (PFC) action, which is done locally at the power plant level.

3.1.1 Primary Frequency Control

The primary control is done locally based on the set-points for frequency and power. These quantities are measured locally, and any deviation from the set values results in a signal that will influence the prime mover of the SG in order to increase or decrease power generation, so that the frequency of the system is kept within acceptable limits. However, due to the proportional control, there will be a steady-state error in the frequency.

The proportional feedback control adjusts the power generation set-point P^* of the generator according to the frequency deviation from the nominal value ω^*:

$$P_m(t) = P^* + u(t) = P^* + K(\omega^* - \omega(t)) \tag{2}$$

Note that the SG turbine dynamics play an important role in the PFC action by introducing time delays in changing the SG output power. The turbine dynamics of thermal power plants can be described using the following model:

$$PFC = \frac{1 + sT_z}{1 + sT_p} K(\omega^* - \omega) \tag{3}$$

Where K is the total primary (droop) control gain and T_z as well as T_p are the time constants of the turbine-governor system.

Consequently, including a PFC action in SGs yields the following frequency dynamics:

$$M \frac{d\omega(t)}{dt} = P_m(\mathrm{t}) - P_e(t) = P^* + PFC(t) - P_e(t) \tag{4}$$

3.2 Dynamics of Power Converters

Today more and more non-synchronous DERs are connected to the power grid and so the frequency dynamics are not solely dependent on the SGs dynamics. In contrast to SGs, DERs do not have inherent response to power imbalances; solar panels have no inertia and wind turbines are interfaced to the grid through power converters hence they are decoupled from the network.

It is worth mentioning that most power electronic converters connected to the grid today are grid-following converters, in other words they require a connection to a strong grid to be able to synchronize and they do not adjust their output power according to the system needs. Such converters can be modelled as loads with negative demand.

In this section, we are mainly interested in the converters that are controlled according to the so-called grid-forming control strategies which have strong influence on the frequency dynamics. In view of the urgent demand for addressing the inertia concern, the focus of this work is on grid-forming converters with virtual inertia (inertial control) provision capabilities, i.e. they change their output power according to the rate of change of frequency, namely the Virtual Synchronous Machine (VSM). For simplicity, in what follows we use the term machine for both SGs and converters emulating SGs.

Virtual inertia can be provided with power *electronic converters* and a proper supplementary *control strategy* to absorb or discharge power from the *energy storage,* as shown in Figure 1.

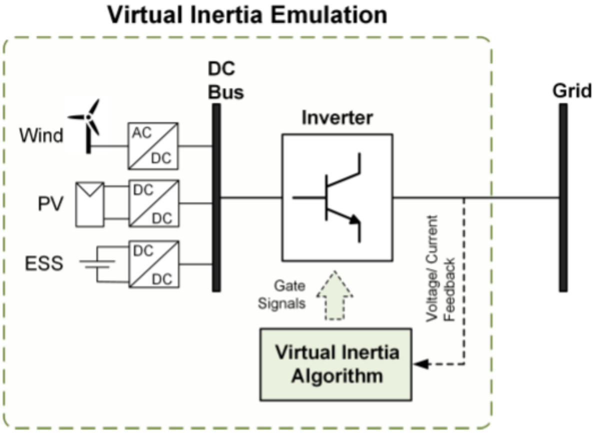

Figure 1 - Virtual Inertia Emulation Concept [9].

For the role of the inertia provision to move from SGs to VSMs, the VSM must emulate the behaviour of SGs based on the power balance of the VSM virtual inertia expressed in terms of the classical nonlinear Swing Equation (1). This results in the well-studied closed-loop behaviour compatible with legacy power systems.

As aforementioned, the structure of the VSM normally consists of energy storage and a power converter equipped with a specific control strategy. The VSM mimics the inertia and damping property of SG so that DERs can support the grid in case of power imbalance and deliver power to the power grid via the converter connected between DC bus/source and the grid. Since the frequency problem is essentially caused by the imbalance of active power, the virtual inertia is realized by controlling the active power as shown in Figure 2.

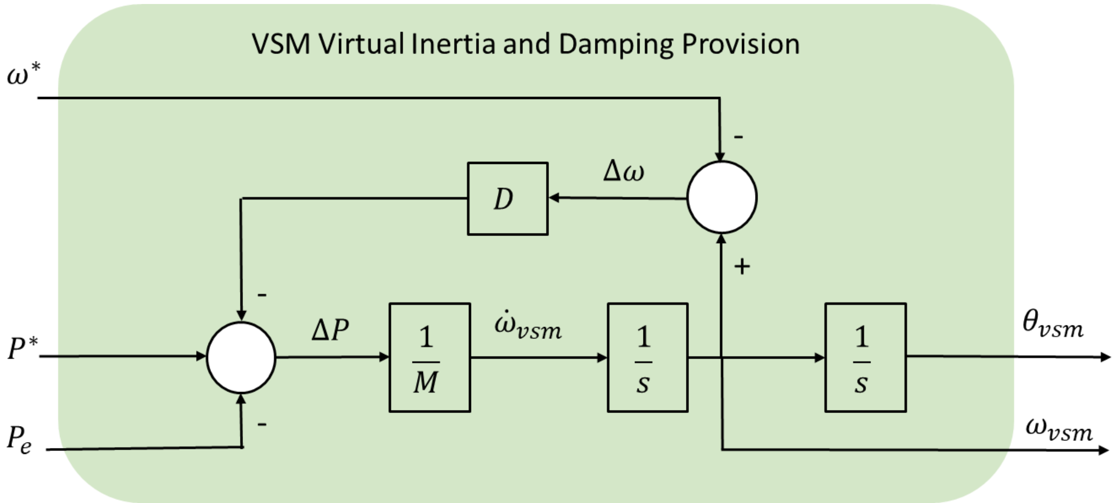

Figure 2 - VSM Virtual Inertia and Damping Provision

Thus, the power balance of the VSM inertia and the VSM phase displacement are defined as follows:

$$M_{VSM}\frac{d\omega_{VSM}}{dt} = P^* - P_e - D_{VSM}(\omega_{VSM} - \omega^*) \tag{5}$$

$$\frac{d\theta_{VSM}}{dt} = \omega_{VSM} \tag{6}$$

Where P^* is the reference input power, P_e is the measured electrical power flowing from the VSM into the grid, while the emulated moment of inertia is defined as M_{VSM} and the emulated damping is D_{VSM}. The internal speed or angular frequency and phase displacement of the VSM are ω_{VSM} and θ_{VSM}, respectively.

As shown, the VSM dynamic behaviour is quite similar to SGs. However, it is worth noting that the damping and inertia coefficients of VSMs are not related to physical properties but rather to control parameters and available amount of energy storage.

The VSM control offers inertial response capabilities and power-balance based synchronization mechanisms. However, SG emulation for virtual inertia provision has drawbacks, such as slower response i.e. longer settling times following a disturbance and undesired low-frequency oscillations that may adversely influence the stability of power systems.

Motivated by these drawbacks, we propose an optimization framework for virtual inertia and damping allocation to improve the oscillations damping and frequency response of the system while minimizing the control effort.

4. Optimization Problem Formulation

As aforementioned, we have developed a two-level optimization algorithm for the inertia allocation of VPPs providing frequency support as an ancillary service to the TSO, as illustrated in Figure 3. The optimization algorithm is meant for scheduling frequency support reserve.

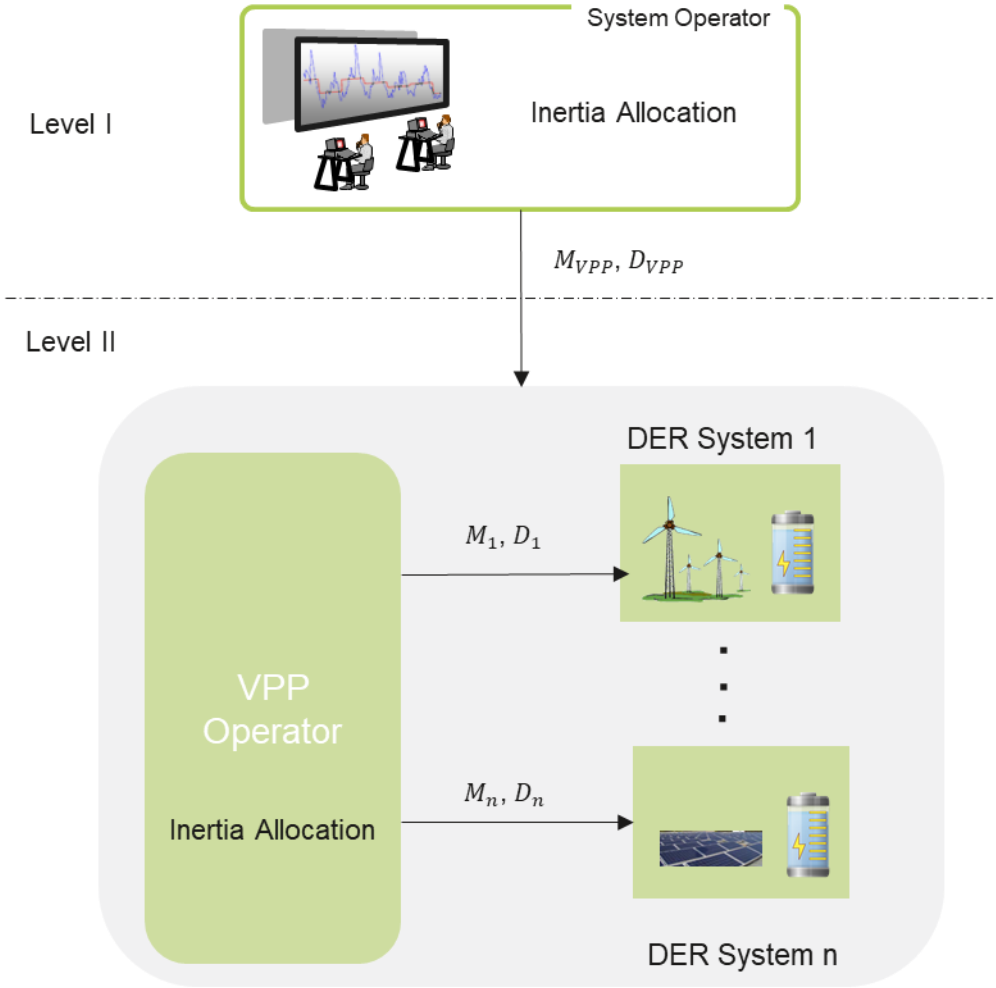

Figure 3 - Two-level Inertia Allocation Algorithm

The modelling of the two-level optimization algorithm will be developed progressively, starting with the formulation of the mathematical model for the optimization at the SO operator level. The objective and the constraints of the first level of optimization will be followed by the mathematical model of optimization problem at the VPP level.

4.1 Inertia Allocation at the TSO

This section briefly describes the formulation of the optimization problem for the allocation of damping from primary frequency control, fast frequency response and virtual inertia from DERs providing inertial response. The objective of this problem is to minimize the total control effort (inertia and damping) required to maintain the stability of the system. Moreover, the optimization is subject to system-level constraints, including dynamic performance and frequency metrics and local constraints for thermal units, such as ramping rates and capacity, as well as for storage units providing fast frequency response and inertia.

The nonlinear optimization problem is solved using sequential linear programming as described in more detail in [10].

Starting with the optimization problem objective, it can be expressed as follows:

$$\min_{M,D} \quad \sum c_D D + \sum c_M M \tag{7}$$

where D and M are the total damping and inertia, respectively.

The optimization constraints are presented in the following subsections.

4.1.1 Frequency Performance Metrics Constraints

The goal of frequency support ancillary services is to contain the initial dynamic evolution of the system frequency following a disturbance within defined security limits.

Three frequency performance metrics are used to set the frequency security limits in case of maximum infeed loss: 1) Rate of Change of Frequency (RoCoF), 2) frequency nadir i.e. maximum frequency deviation, and 3) quasi-steady-state frequency deviation.

4.1.1.1 Rate of Change of Frequency Constraint

The maximum RoCoF occurs immediately after a disturbance; initially the frequency excursion is only limited by the inherent inertial response of synchronous generators. In the first interval of inertial response, the frequency control actions from PFC and FFR are negligible.

Hence, the maximum value of the RoCoF is proportional to the power imbalance and inversely proportional to the system inertia; this suggests that the minimum level of system inertia, required to satisfy the maximum RoCoF requirement is obtained as:

$$M_{min} = \frac{\Delta P}{RoCoF_{max}} \tag{8}$$

4.1.1.2 Frequency Nadir Constraint

The frequency nadir is defined as the maximum frequency deviation reached during the transient period after a disturbance. The nadir depends on the system inertia and the frequency response from synchronous generators and converters providing frequency support to the system.

The frequency response from the PFC and FFR, is assumed to be linearly increasing with time and thus characterized by a fixed slope until the reserve R_j is fully activated at T_j.

Hence, the aggregated frequency response $FR(t)$ is a piecewise linear function:

$$FR(t) = \begin{cases} \sum_{j=1}^{N} \frac{R_j}{T_j} t & t < T_1 \\ \frac{R_1}{T_1} + \sum_{j=2}^{N} \frac{R_j}{T_j} t & T_1 < t < T_2 \\ \vdots & \\ \sum_{i=1}^{n} \frac{R_i}{T_i} + \sum_{j=n+1}^{N} \frac{R_j}{T_j} t & T_n < t < T_{n+1} \\ \sum_{j=1}^{N} \frac{R_j}{T_j} & T_N < t \end{cases} \tag{9}$$

Including the aggregated frequency response into the aggregated system frequency dynamics, yields the following frequency dynamics:

$$M\frac{df(t)}{dt} = P_m(\mathrm{t}) - P_e(t) = \Delta P + FR(t) \tag{10}$$

Subsequently, the frequency nadir can be derived from the time evolution of the aggregated frequency reserve. The system is assumed to be at nominal frequency pre-disturbance. By integrating the frequency dynamics the time when the frequency nadir occurs can be calculated and then the frequency nadir can be derived as follows:

$$\Delta f_{nadir} = \frac{(\Delta P\text{-}R_{full})^2}{2 * \sum \frac{Rj}{Tj}} * \frac{50}{M} + \frac{\sum RiTi}{2} * \frac{50}{M} \tag{11}$$

More details on the mathematical derivation are found in [10]. The maximum frequency deviation should not exceed the predefined threshold by grid codes.

$$\Delta f_{nadir} < \Delta f_{nadir,max} \tag{12}$$

4.1.1.3 Quasi-Steady-State Frequency Constraint

Unlike the previous two constraints, the quasi-steady-state frequency deviation does not depend on the system inertia. It depends essentially on the total amount of the frequency response delivered when the frequency reaches a steady-state value.

$$\Delta f_{ss} = \frac{\Delta P}{D} \tag{13}$$

This defines the minimum required frequency response i.e., damping reserve to satisfy the maximum quasi-steady-state frequency deviation Δf_{ss}.

4.1.2 Small-signal Stability Constraints

Another stability aspect that is of great importance for TSOs is the oscillatory small-signal stability which determines the ability of machines in the power system to remain synchronised or return to synchronism after small disturbances. Small-signal stability can have long-range interactions with inter-area mode oscillations or local mode oscillations:

- local-area modes: associated with a single synchronous generator or a small group of generators and typically are in the range of 0.7 to 2.5 Hz.
- inter-area modes: associated with large groups of machines across the system swinging against each other. These modes are typically in the frequency range from 0.1 to 1.2 Hz.

These low-frequency oscillations need to be properly damped and decrease with time.

As the disturbances under consideration are small, the system model can be linearized around the operating point and modal analysis can be performed yielding the eigen-values (corresponding to oscillation modes) of the system $\lambda_{1,2}$:

$$\lambda_{1,2} = -\omega_n(\xi \pm i\sqrt{1-\xi^2}) \tag{14}$$

Where ξ is the damping ratio of the mode and ω_n is the undamped frequency of the mode.

For acceptable dynamic performance, we introduce the following constraint on the damping ratio of the modes:

$$5\% < \xi \tag{15}$$

4.1.3 Local Constraints

The allocation of inertia and damping is also subject to local physical constraints of generation units. Each generator or energy storage can deliver a maximum amount of frequency reserve, R_i, limited by its power rating, $P_{max,i}$, and the current loading level, $P_{g,i}$.

$$P_{g,i} + R_i < P_{max,i} \tag{16}$$

4.2 Inertia Allocation at the VPP

Using the aforementioned optimization algorithm (7)-(16), based on contingency analysis, the TSO determines the total aggregated inertia and damping the VPP shall provide at the point of coupling with the transmission system.

The TSO communicates these required effective inertia and damping quantities. Subsequently, the VPP coordinates the amount of inertia and damping of individual DERs in order to fulfil the TSO requirements.

The second level of the optimization framework, involves an allocation algorithm for VPPs to disaggregate the effective inertia and damping into individual DER contributions taking into account the constraints of these DERs with the objective of minimizing the total cost for the VPP to meet the TSO request.

At this level of optimization, the problem is formulated as follows:

$$\min_{M_i, D_i, i \in VPP} \quad \sum c_D D_i + \sum c_M M_i \tag{17}$$

s.t.

$$\begin{gathered} \sum D_i = D_{VPP} \\ \sum M_i = M_{VPP} \\ \underline{P_i} \leq P_i \leq \overline{P_i} \\ \underline{E_i} \leq E_i \leq \overline{E_i} \end{gathered} \tag{18}$$

The equality constraints ensure that the VPP allocates the total amount of damping and inertia requested by the TSO. On the other hand, the inequality constraints present the physical limitations of the energy storage and ensures that the allocated reserve for each energy storage limit does not exceed the rated power P_i and the rated energy E_i.

4.3 Use Case and Results

The proposed optimization algorithm is evaluated on the linearized numerical model of the New England IEEE 39-bus benchmark system. In the context of the rapid increase distributed energy resources penetration, the IEEE 39-bus system is modified to represent a future scenario of a power system with VPP providing frequency control (see Figure 4). The VPP includes an aggregation of DERs that provide controllable virtual inertia and damping.

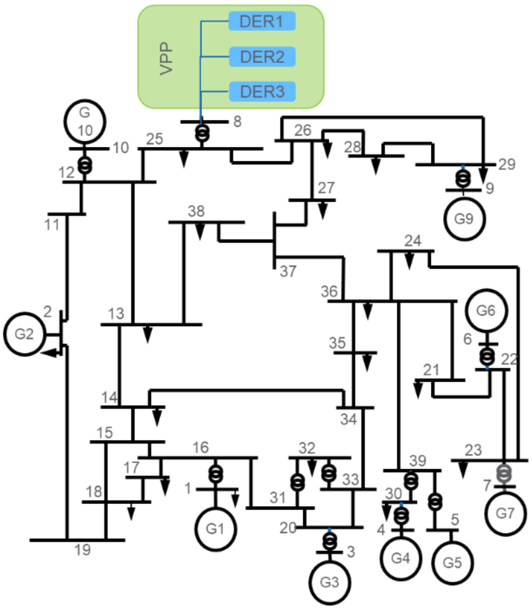

Figure 4 - The Modified 39-bus System

First, we investigate the relevance of the allocation of reserve services. Then, we present two case studies to validate the proposed optimization framework.

4.3.1 Relevance of Frequency Response Spatial Allocation

In this example we compare the impact of two spatial distributions of frequency response on the frequency dynamics of the system. It is worth mentioning that

First, we increase the amount of damping randomly at three different buses in the system.

In the second case, without using the optimization algorithm developed within edgeFLEX, we try to make an educated guess regarding the spatial allocation of damping that could improve the system dynamic response.
With that aim, we perform eigen-value analysis of the system and calculate the eigen-values and the right eigen-vectors of the slowest modes μ_2, μ_3. The magnitude of the right eigen-vectors provide information regarding the observability of the modes at different buses in the system.

Table I - The observability of the slowest oscillations modes (μ_2, μ_3) at different buses

Bus no.	$u(\mu_2)$	$u(\mu_3)$
1	0.14	0.35
2	0.01	0.01
3	0.012	0.02
4	0.051	0.008
5	0.65	0.0001
6	0.005	0.0003
7	0.005	0.0003
8	0.041	0.0034
9	0.065	0.6
10	0.017	0.0006

Consequently, in the second case we apply the same amount of damping added in the first case but at buses (1,5 and 9) where the slowest modes are more dominant, as illustrated in Table I. The random distribution has resulted with a maximum deviation in the system frequency of 200 mHz in contrast to the second case that resulted with a maximum frequency deviation of 187 mHz for the same disturbance, resulting in an improvement of 6.5%.

In this simple example, without running any optimization algorithm to allocate the damping and inertia, we showed that the spatial distribution and not only the total frequency reserve (damping and inertia) is relevant for the system performance and stability.

In the following sections, we apply and validate the inertia allocation algorithm.

4.3.2 Case Study I: 100% Penetration of Converter-Interfaced Generation

In this case study, the modified IEEE 39-bus system includes a 100% penetration of converter-interfaced generation with controllable virtual inertia and damping coefficients as described in section 3.2. The goal of this case study is to investigate the system requirements in terms of inertia and damping in general.
We assume that the damping and inertia coefficients of all converters are tuneable and associated with a cost and apply the optimal inertia allocation algorithm to scenario IA_A, described in section A.1.1, representing the inertia allocation at TSO level. In Figure 5 and Figure 6, we compare the base case unmodified IEEE-39 bus system [8] with the system after the optimal allocation of inertia and damping.

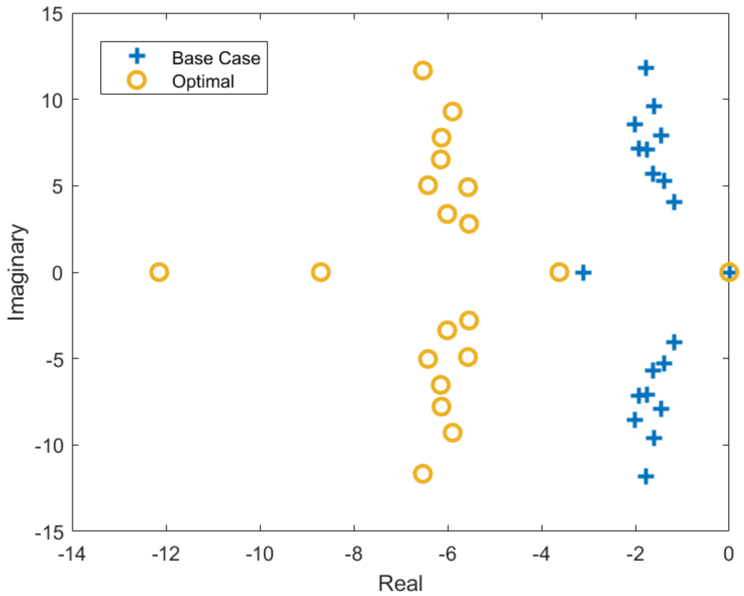

Figure 5 - Case Study I: The System Eigen-values

Figure 5 illustrates the performance of the inertia allocation algorithm and the resulting improved dynamic performance; represented with faster modes (i.e., larger negative real parts of the eigen-values) and higher damping ratios.

Using (14) to calculate the damping ratios (ξ) of the modes, we observe that the minimum damping ratio is increased from 14.8% to 48.8%.

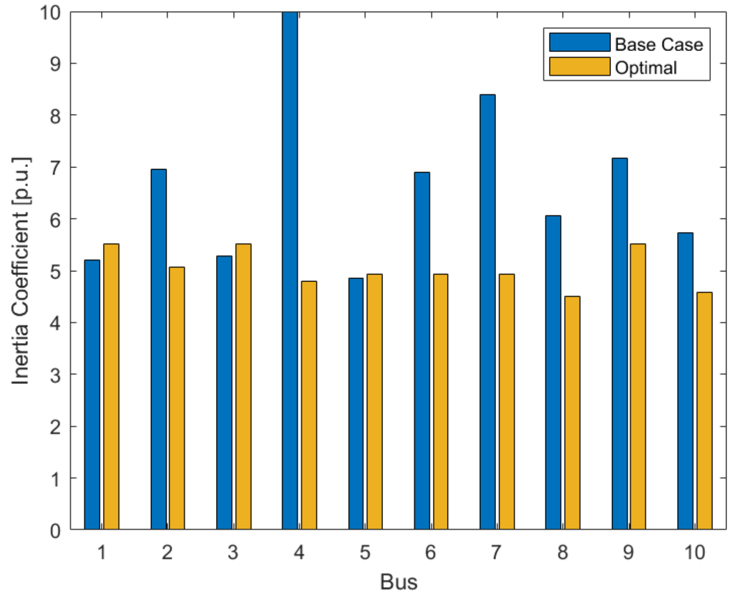

Figure 6 Case Study I: Inertia Distribution

The inertia distribution resulting from the optimal inertia allocation algorithm compared to the base case inertia distribution is shown in Figure 6. As depicted, the optimization results in a more uniform and thus robust allocations.

4.3.3 Case Study II: 40% Penetration of Converter-Interfaced Generation

In this case study, the modified IEEE 39-bus system includes a 40% penetration of converter-interfaced generation with controllable virtual inertia and damping coefficients. In particular, the synchronous generators connected to buses 8, 9, 10 and 5 are substituted by an aggregation of converter-interfaced DERs. Moreover, the DERs at bus 8 constitute a dynamically controlled VPP as presented in Figure 4.
The proposed two-level optimization framework for TSOs and VPPs, by considering scenarios IA_A and IA_B (see Section A.1.1 of the ANNEX) is evaluated in this case study.

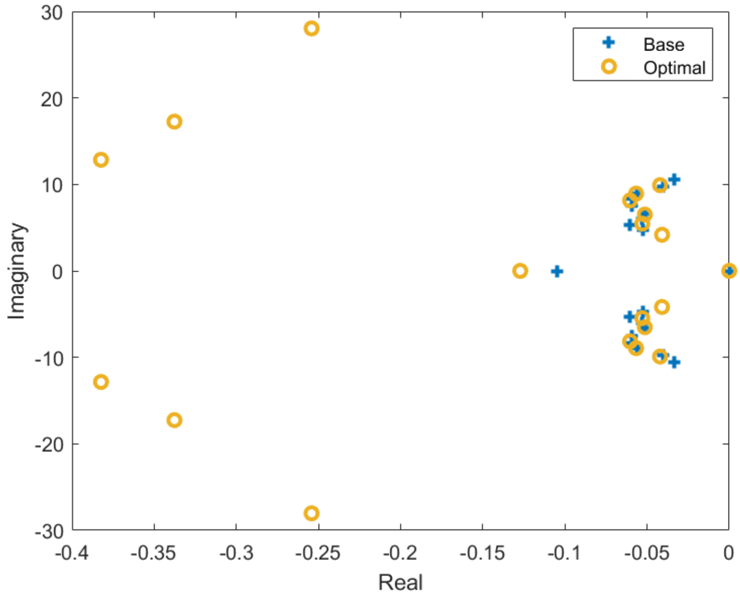

Figure 7 - Case Study II: The System Eigen-values

The first level of optimization at the whole system level results in an improved dynamic response of the system as illustrated in Figure 7. The optimal inertia allocation of the converter-interfaced generation and the damping, resulting from the frequency response, of all machines increases

the damping of the slowest mode and results in faster modes. Thus, enhances the small-signal stability of the system.
Figure 8 compares the damping distribution in the base case to the optimal case. In the base case, a uniform allocation is assumed, however the optimal allocation results in more damping at bus 1 and 5. As for the inertia allocation, it is assumed that the synchronous generator inertia is fixed, due to the fact that the mechanical inertia is a fixed physical parameter in contrast to the virtual inertia emulated by converters. Hence, we can only allocate the inertia at buses 5,8,9 and 10. The inertia distribution resulting from the inertia allocation algorithm is presented in Figure 9. It can be noticed that the optimization resulted in more inertia at bus 5.
These results are in line with the conclusions presented in section 4.3.1; more frequency support is needed at the buses where the slow system modes are more observable.

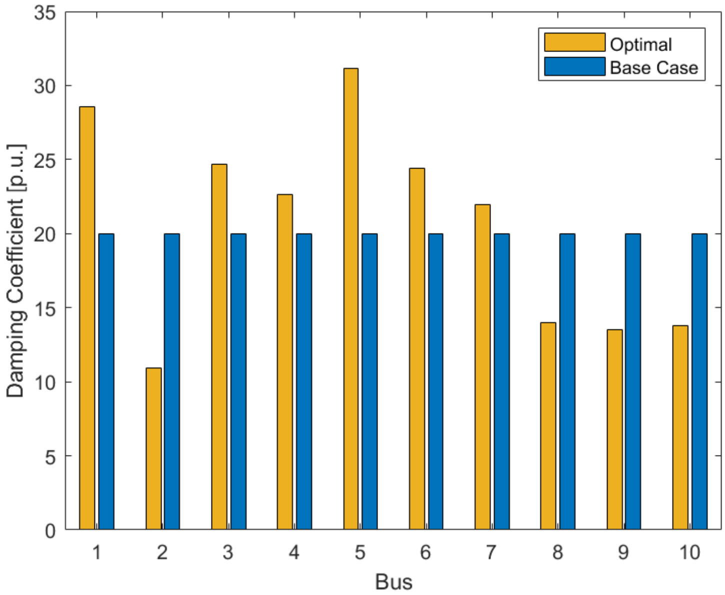

Figure 8 - Case Study II: Damping Distribution

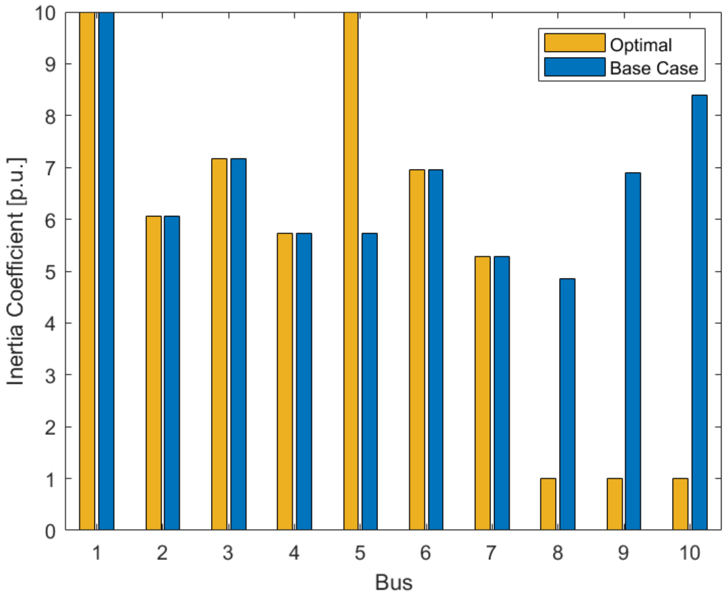

Figure 9 - Case Study II: Inertia Distribution

The first level of optimization results in the amount of inertia and damping required from the VPP at bus 8. The second level of optimization at the VPP allocates the total requested inertia and damping to the three DERs constituting the VPP.

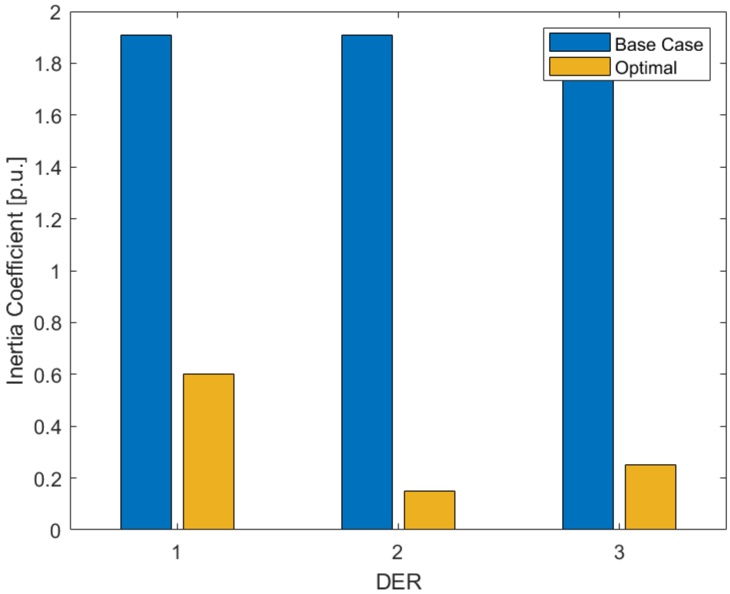

Figure 10 - Case Study II: VPP Inertia Distribution

Figure 10 shows the inertia distribution for the DERs compromising the VPP. For the sake of simplicity, in the base case it is assumed that the total virtual inertia provided by the VPP is shared equally between the different DERs. Based on the requested inertia, resulting from the first level of optimization, the second optimization level allocates this amount between the different DERs with the objective of minimizing cost and taking into account the local constraints related to the operating point and the physical properties of the storage.

5. Conclusion

This deliverable presents a two-level optimization framework for allocation of inertia developed for TSOs and future VPPs. The first optimization level is intended as a scheduling tool for the TSO to allocate the required inertia and damping in different parts of the system with the objective of improving the dynamic performance of the system and ensuring its security. The second level of optimization is for the VPP to disaggregate the total inertia and damping requested by the TSO between the different DERs that comprise the VPP and provide frequency response. The objective of this allocation algorithm at the VPP level is to minimize the cost of frequency response provision for the VPP.

The test results described in Chapter 4 indicate that the inertia allocation framework developed within task 2.5, improves the system dynamic performance; represented with higher damping ratios and faster modes. Additionally, it ensures that the post-fault dynamic frequency requirements in terms of rate of change of frequency, frequency nadir and quasi-steady-state frequency are fulfilled.

Furthermore, we demonstrate the relevance of spatial allocation of frequency response in the system. Hence, the proposed optimization framework is a useful tool for efficient and more-informed inertia allocation scheme.

6. List of Tables

7. List of Figures

8. References

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9. List of Abbreviations

FFR	Fast Frequency Response
RES	Renewable Energy Sources
SO	System Operator
TSO	Transmission system Operator
VSM	Virtual Synchronous Machine
DER	Distributed Energy Sources
VPP	Virtual Power Plant
ESS	Energy Storage System
SG	Synchronous Generator
PFC	Primary Frequency Control
RoCoF	Rate of Change of Frequency

ANNEX

A.1 Inertia Allocation Scenarios and Requirements

A.1.1 Inertia Allocation Scenarios

In total, there are two scenarios studied in edgeFLEX concerning the inertia allocation in power systems as presented in Figure 3. The scenarios differ in terms of the main actors and optimization objective.

In IA_A, the inertia allocation scheme is meant for the TSO to allocate virtual inertia and damping, in power systems that include conventional synchronous generators and converter-interfaced DERs generation with the objective of improving the dynamic performance and maintaining the frequency stability of the overall system.

In contrast, the research work for IA_B addresses the inertial control allocation at the VPP level with the objective of disaggregating the total inertia and damping allocated to the VPP by the TSO and allocating it to the different DERS constituting the VPP in the most economical way.

The scenarios summary is presented in the following table:

Table II- Inertia Allocation Scenarios

Scenario	Title	Description
IA_A	Inertia Allocation at Transmission Level	Optimal placement of virtual inertia and damping at the transmission system level with the objective of maintaining the system stability.
IA_B	Inertia Allocation at VPP Level	Optimal placement of virtual inertia and damping at VPP level with the objective of minimizing the overall cost for the VPP.

The researchers in WP2 expect that the investigation and results will be applicable in future power systems (2030+), with increased penetration level of DERs providing virtual inertia and fast frequency response as an ancillary services.

A.1.1.1 Functional Requirements

- **Objective:** planning the optimal placement of virtual inertial control and damping.
- **Timeframe:** hourly basis following the scheduled re-dispatch of the generation or power set-points.
- **Measurements:** no measurements are needed.
- **Manner:** The inertia allocation is to be executed at the control center of the TSO or the VPP.
- **Information exchange between operators:** The TSO sends the allocated value of virtual inertia and damping to the VPP.
- **Data Recordings:** Data storage of system data, parameters and dynamic models is required.

A.1.1.2 Information Exchange and Communication aspects (performance requirements)

The inertial control allocation is an optimization framework used for power system planning and scheduling, hence it does not have stringent performance and security requirements as compared with real time control. The following table summarizes the ICT requirements:

Table III - Inertia Allocation Communication Requirements

Performance Requirement	Description
Measurements Sampling Rate	N/A
Latency	The optimization algorithm will run on hourly basis, hence communication delays are not critical.
Data Volume	A total of 2 quantities (virtual inertia and damping) to be sent from the TSO to the VPP in IA_A. A total of 2 quantities (virtual inertia and damping) to be sent from the VPP to the DER in IA_B. Each measurement quantity is of type float.

The above mentioned requirements are applicable to the different use cases and commercial rollout.

IA_A General Description

Scenario IA_A considers the inertial control allocation by the TSO. According to the generation mix we can see at the high-voltage level, we would have both conventional generators (hydro, thermal, nuclear) and also converter-based DERs generation. Therefore in IA_A we have considered inertia allocation for DERs and damping allocation for both DERs and SGs. We consider the following use cases:

- The modified IEEE 39-bus system with 40% and 100% penetration of DERs with controllable virtual inertia and damping.

The inertial control allocation algorithm in IA_A has the following component requirements:

- Generating Units: Conventional synchronous generators and/or RESs generation with Energy Storage Systems (ESSs) allowing the RESs to provide frequency control support including primary control and inertial control.
- Power Converters: The power converters provide the interface between the grid and the different DERs. These converters must have control strategies that enable the RESs to provide frequency control support including primary control and inertial response.
- Data storage and Energy Management System (EMS) at the control center of the TSO to collect the system data, perform eigenvalue analysis and run the inertial control allocation algorithm.

The TSO is responsible for maintaining the stability of the grid facilitating the deployment of new efficient services.

Accordingly, in IA_A, the main actor is the TSO that will run the inertia allocation algorithm with the objective of maintaining the grid stability and ensuring sufficient amounts of inertia and damping in the system.

IA_B General Description

Scenario IA_B focuses on the inertia allocation at the VPP level to ensure economical operation by minimizing the total cost of providing inertial control while ensuring meeting the physical constraints of the DER units.

Consequently, the main actor in IA_B is the VPP operator and the inertia allocation algorithm has the following component requirements:

- Generating Units: DERs generation with Energy Storage Systems (ESSs) allowing the DERs to provide frequency control support including primary control and inertial response.
- Power Converters: The power converters provide the interface between the grid and the different DERs. These converters must have control strategies that enable the DERs to provide frequency control support including primary control and/or inertial response.