No 727481 RESERVE

D1.4 v1.0

Use Case Definition for Research in Frequency and Voltage Control

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Abstract:

This deliverable is an intermediate report of the use cases definition, depicting in general the system needs from the perspective of energy system requirements and functions, ICT architectures. Based on the input from D1.2 and D1.3, and control techniques developed in WP2 and WP3, this deliverable provides a tentative discussion on possible new actors and their roles under two implementation schemes (i.e. market-based mechanism and regulation-based mechanism).

Keyword list:

100% RES Energy Networks, voltage and frequency control scenarios

Disclaimer:

This deliverable is mainly a synthesis of the work reported in the other deliverables. The actors and their relevant roles discussed in this deliverable are initial proposals from WP 1 which may be subject to change following further discussion in the project as a whole.

Executive Summary

This deliverable D1.4 presents the work of *Task 1.4 definition of reference use case scenarios* within the wider context of work package 1 and the RESERVE project. This deliverable had planned to use the input of *Task 1.2 requirement placed on power systems by transitions to 100% RES* and *Task 1.3 requirement on scalable ICT for energy systems with 100% RES* to define use cases which would be used as input for the work in WP2 and WP3 to support the definition of the voltage and frequency concepts.

However, the identification process of the scenarios deeply involved partners from WP2 and WP3; therefore, the scenarios have already reflected their research needs for both frequency and voltage control. This deliverable is mainly a synthesis of the work reported in the other deliverables.

Two scenarios for the study of frequency have been identified: *Sf_A mixed mechanical – synthetic inertia scenario* and *Sf_B only synthetic inertia* scenario. In the first scenario, a coexistence of Synchronous Generators and Converters is identified. Storage such as (batteries, flywheels) or a renewable generator should provide the needed power for the converter to provide synthetic inertia. In Sf_B only converter-based generation and consumption are assumed. This means that frequency becomes an artificial signal set by converters' controllers. We have therefore the possibility to introduce simpler dynamics ("Linear Swing Dynamics"), which will be studied in WP2. The idea is to mimic the SGs but simplify all the non-linear dynamics.

Similarly, two scenarios for supporting the voltage study were designed. *Sv_A dynamic voltage stability* is defined for the study of the voltage stability and the corresponding control techniques in a short-term. By contrast, *Sv_B active voltage management* is designed to consider a system-wide mid-term voltage control to harmonize current control practice with new methods.

This deliverable is an intermediate report of the use cases definition, depicting in general the system needs from the perspective of energy system requirements and functions, new actors and new roles, ICT architectures for supporting these actors, as well as possible implementation schemes.

The design of these scenarios was performed through the SGAM techniques. In D1.2 and D1.3, the requirements of the energy systems and the ICT, the physical layer, function layer, the information and communication layer have been developed.

To successfully apply the technologies developed in the RESERVE project, the implementation scheme and the involved actors are essential. Therefore, this deliverable put the focus on discussing the two most possible schemes, i.e. through market-based mechanisms and through regulations (network codes).

For the frequency, if we assume a market mechanism to share the needed reserves, we need to define the roles of new entities like aggregators, virtual power plant, electric vehicles, prosumers. Moreover, we also need to understand if and how the DSO intervenes in the frequency control because most of the new entities are located in the distribution grids. This deliverable provides some preliminary discussion. Later *WP6 regulatory, legal and business models for RES* will make a detail description.

For the voltage scenarios, even though market-based mechanisms (if such market will be set up) can get clear economic signals through competition for the services inverters provide; it is difficult to quantify and price the services. Thus, the regulation-based implementation scheme may be more applicable in the near future. Consequently, the RESERVE project is dedicated to propose new network codes or relevant modifications so that the voltage issues of the distribution grids can be resolved when facing 100% renewable.

In order to avoid the repetition of information on the use cases (reported in *D1.2 Requirements placed on energy systems on transition to 100% RES* and *D1.3 Requirements placed on ICT for energy systems with up to 100% RES*) that are under development in other WPs, e.g. *WP2 frequency stability by design, WP3 voltage stability by design, WP5 Test-beds for validation of research results*, we simply refer to them when needed.

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1. Introduction

1.1 Scopes of the deliverable

This deliverable is the output of Task 1.4 in WP1. This task extends the work of T1.1 to include the implementation schemes for the identified scenarios of frequency control problems (SF_A and SF_B) and voltage control issues (Sv_A and Sv_B).

During the design of the scenarios, partners from WP2 and WP3 for the study of the control techniques for frequency and voltage are deeply involved. Therefore, the identified scenarios are aligned with their research needs and methodologies.

This deliverable describes the energy system changes in the future with special focus on the aspects of frequency and voltage. Consequent issues caused by these changes are also discussed. Firstly, new requirements and needed functions are introduced with respect to solving the issues in the new scenarios. Emerging actors or roles to take care of these new functions are briefly described. Corresponding ICT architectures among actors by considering the two different implementation schemes are tentatively introduced. Some preliminary arguments on the possible markets and relevant roles are discussed. The final definition of the actors and business model will be built in WP6, here we simply try to draw the attention on the most important points from the Energy and ICT point of view. The RESERVE scenarios are still evolving: researches in WP2 and WP3 and field trial in WP5 will later give us fundamental hints to change the basic architectures of the scenarios. The updated information will be reflected in D1.5.x periodically.

In order not to repeat what other deliverables have documented for the use cases, we link them to the implementation structures presented in this deliverable and give references to them when needed. In general, Energy and ICT requirements of the scenarios are already well described in D1.2 and D1.3. In D1.4, we focus on new roles and possible implementation schemes to complete the scenarios.

1.2 How to read this deliverable

This deliverable needs a clear comprehension of arguments in D1.2 and D1.3 where scenarios and uses cases are already presented from Energy and ICT perspective. However, information from WP2, WP3, WP4 and WP5 are also used. Overall, this deliverable is related to the following documents from the RESERVE project:

1) D1.1 Scenarios & architectures
2) D1.2 Energy system requirements for the Scenarios
3) D1.3 ICT requirements of the Scenarios
4) D2.1 and D2.2 for frequency study and research concepts
5) D4.1 for presentation of the Pan european Lab infrastructure
6) D3.1 and D3.2 Voltage control theorems and algorithms
7) D5.1 Field trials presentation for voltage and frequency control concept
8) D5.4 for the WAMS Romanian System presentation

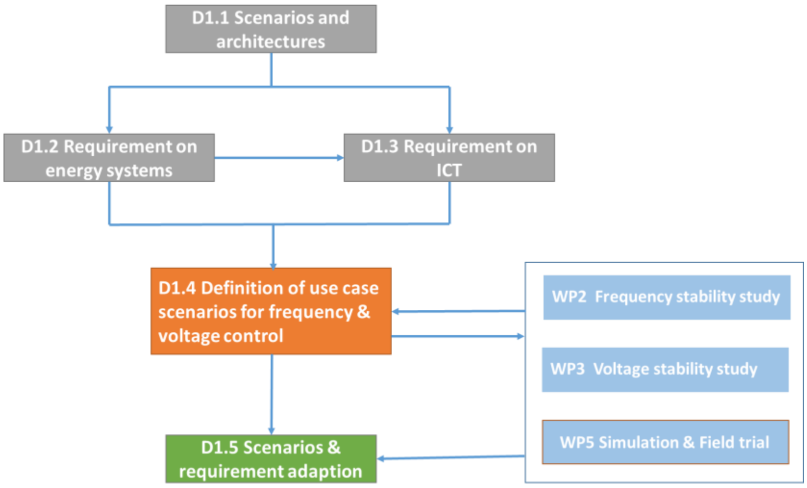


Figure 1 Relations among deliverables in WP1 and other WPs

The above mentioned deliverables will be cited in the text of this work, when their knowledge is needed.

Figure 1 describes the relations of this deliverable to the other deliverables in the WP1 and other WPs. With the deep involvement of partners from WP2 and WP3, the identified scenarios have been tailored for the study needs of WP2 and WP3 for system frequency and voltage stability. The energy system requirements are described in *D1.2 requirements placed on energy systems on transition to 100% RES* while the information and communication requirements are reported in *D1.3 requirements placed on ICT for energy systems with up to 100% RES.* This deliverable took input from D1.2 and D1.3 to further develop other aspects of the scenarios. All the information will be updated further in *D1.5 Adaption of research concepts based on simulation, live ICT tests and field trial results* as the research and trials progress inside the RESERVE project.

1.3 Deliverable contributions

Based on the identified scenarios and control issues in an active grid with 100% RES, possible implementation structures are discussed, i.e. through market approach or regulation approach.

The two frequency scenarios are referred to the future system: in Sf_A there is still mechanical inertia provided by Hydro Power Plant, while in Sf_B there is no more mechanical inertia but only converter-based generation.

On the other hand, the voltage control scenarios address the dynamic stability and harmonic distortions under high penetration of converter-based loads (Sv_A Dynamic Voltage Stability Monitoring) and the global voltage control to avoid congestions in the distributions grids (Sv_B Active Voltage Management).

In this deliverable, the involved actors and their roles are tentatively introduced under different implementation schemes. This could be a starting point to discuss the sustainability of the techniques studied in the RESERVE project.

2. Use cases for frequency control

In this chapter, we enrich the use cases of D1.2 and D.1.3 from the point of view of frequency control. We discuss possible options and evolution of the use cases in terms of new functions, ICT and implementation schemes. How RESERVE studies link to all the discussion are summarized at the end.

2.1 Change towards the futuristic power system

In the RESERVE project, we consider two scenarios for the frequency:

Scenario Frequency A (SF_A): called Mixed Mechanical-Synthetic Inertia Scenario. All connection categories are present into the grid, but only hydro power plant represents the Synchronous Machine connection.

Scenario Frequency B (SF_B): called Synthetic Inertia Scenario. Only converters are present into the grid

These scenarios (or use case) have a great theoretical and practical value.

Traditional frequency control in current ENTSO-E network codes 15) in the future will not be able to cope with the decreasing inertia. In the future, only using the remaining hydro power plants will probably not be able to keep the grid stability. It will be more complex but maybe much cheaper to introduce new resources such as prosumers, storage and DER into the frequency control schemes.

Annex A.1.1 gives more details about the changes in the future power system from the perspective of frequency.

2.2 Scenarios design corresponding to the changes

In D1.2 and D1.3 of RESERVE, the scenarios Sf_A and Sf_B are described in detail in terms of technological requirements (the components and relevant functions) and ICT requirements (communication architectures, information to be exchanged with expected performances and security requirements). The goals for both Sf_A and Sf_B are linked to each other. Many common points can be found in the research concepts and validation trials of both.

2.2.1 Sf_A: Mixed Mechanical-Synthetic Inertia Scenario

Description in detail of this scenario is in chapter 3 of D1.2 and chapter 3 of D1.3.

2.2.1.1 Basic description of new components and functions

The system which we are addressing is the one to which we expect the European system will evolve in next years and possibly at the end of the de-carbonization process. The system will be composed mainly of hydro, PV and wind generation sources. Consumers will gradually transform into prosumers (private, commercial and industrial entities) which will have some degree of control in their load profiles thanks to automation development and could also become net injector into the grid in the presence of PV-distributed sources present in their portfolio of assets. The frequency dynamics will be based on the **natural mechanism of the mechanical inertia of the grid** like today, while the value of inertia into the grid will be very low compared to today's standards, and therefore additional resources will be needed to limit the frequency swings. New resources will be used for this reason, but they will interface to the grid via a converter. From a world dominated by synchronous machines, asynchronous motors, and classical loads, we are going towards converter-dominated power systems.

In Sf_A. the converter-based resources will participate in the classical primary and secondary control loops: as inertia is decreasing, new recommendations on the time frames of the controls need to be investigated. Moreover converters will enable the grid to introduce Rate of Change of frequency (RoCof) control. This new form of control emulates the physical inertia of the synchronous machines. The converter will respond to the derivative of the frequency signal, delivering more or less power (please refer to D 2.2 for more details), mimicking the releasing or accumulation of kinetic energy.

Secondly, if converters is used for active power control, there should be some sources of energy that sustain such control. In the case of batteries, it will be the residual power to contribute to the frequency control. In the case of PV and wind sources, it is possible to adjust the work point below the maximum power point in such a way to leave some reserves 1). This is helpful for grid stability but it is a waste of renewable energy and should be carefully considered. In the case of demand response, industrial processes or thermal inertia of buildings can be exploited.

Consequences on System Control Structure: converters (see A.2 for the roles of the converter) will now need to locally monitor frequency levels, or be able to receive commands from distributed command units as fast as possible. In D1.2 and D.1.3, all the variants are extensively studied. The technical and particular control law that will be studied are currently in development in WP2 (first definitions can be seen in D2.1 and D2.2).

In D1.3, three fundamental architectures of communications were devised: centralized, distributed, and decentralized, which also apply to the physical structure of the power grid. The ICT and implementation schemes will somewhat influence and be influenced by the architectures. There is no right or wrong architecture. The best architecture depends on several factors like costs of new assets, difficulties of regulatory transition, smooth or hard shifting of roles, technical possibilities, etc.

Secondary Control will remain as a Centralized Control in RESERVE: The TSO (through the Energy Management System) will centrally compute the needed reserve and communicate it to all the involved parties. Thus the TSO is able to address the problem of frequency and power import/export deviation, and to avoid the problem of confliction in a non-centralized system. In the case that distributed resources participate in this ancillary service, the reserve level will be communicated through the DSO (using the Distribution Management System). For primary and inertial control, both decentralized and distributed architectures can be used. The three types of power system architecture can be seen in D1.3.

Decentralized control does not need the communication among devices, but it depends on local measuring. In general, it is simple and less costly.

Distributed control needs local measuring and control points which will communicate the RoCof to the involved units. Before sending out the RoCof, the unit could also first compute the power levels of various resources and then communicate the results with the involved resources and the system operators. This could avoid the error of local measurements when low quality measurement units are used and give inconsistent orders in case of particular or strong dynamics. As explained in D2.1**,** in the future we expect less stable frequency. There will be no monolithic frequency signal, and differences in frequency among various nodes are non-negligible. The control points and system operator could eventually communicate between each other to improve the quality of frequency control or to communicate the frequency reserve obtained from ancillary markets if defined.

Commonly, these systems connecting various PMUs with a central server are called Wide Area Measurement Systems (WAMS). Inside the RESERVE project we are going to make use of the Romanian WAMS both in simulations and field trials (D 5.4).

Finally, a distributed system can easily adopt the VPP, load aggregator and micro-grid, which could be monitored and controlled through a distributed communication system, allowing for a direct dialogue. WP6 will clearly define these new actors in terms of characteristics and roles in the framework of RESERVE project.

2.2.1.2 Actors and their new role

As can be seen in D2.2, the major resources that will be investigated in Sf_A are bulk storage in the transmission grid like batteries or flywheels or supercapacitors. They all feature advantages and disadvantages, but nowadays batteries seem the most promising technology to enter the electric grid market thanks to their falling costs. In particular, Lithium Ion batteries are the ones which have better efficiencies and lower costs. The work in RESERVE will concentrate on the use of batteries and the relevant effects in the electric grid.

New distributed resources, usually present in the distribution grid, will be grouped as equivalent large units and then possibility to offer frequency reserves for the grid. Usually they are considered as Virtual Power Plant.

Loads are gathered by load aggregators to provide technical support for frequency control, and may be used to enhance the operation of new markets (if exists) in the future.

Some basics description of what will be the role of these and other emerging actors with respect to Sf_A and Sf_B is discussed in section 3.5 of D1.2. Support needed from emerging actors can be found in D1.3 section 2.1 and section 2.1 of this deliverable. Sf_A, in particular, is a scenario in which the solutions proposed can be considered as innovative and necessary for the transition of power systems.

In RESERVE, WP6 will provide a clear description of actors and their relationship inside the four basic scenarios, starting from the simulation and validation trials, which will consider also business and market dimensions. The description in this deliverable will be preliminary and limited to the scenarios studied in RESERVE (frequency and voltage control, in a short/medium time frame).

The implementation scheme of the frequency control will surely depend on the way the power system is organized. Power system could be operated in a way like centralized, distributed or decentralized. Similarly, markets for ancillary services or the regulation regime can be organized in a centralized, local or distributed fashion. As new actors enter the market, their relative and best position are still in strong debate.

The scheme of the frequency control services (dividing between inertial and primary response and secondary frequency control) can be subject to a market or be treated as regulated service (like for example the primary frequency control today). WP2 and WP3 will provide clear technical results during the second year of the project such that WP6 can clarify the RESERVE view on these new frequency services.

If we assume that new forms of inertia, primary and secondary control come from competitive markets, then several market structures are possible.

On the other hand, regulation scheme could also be considered as an alternative that every asset should provide such control services, following some technical requirements.

In RESERVE, we are approaching the problem by considering the possible actors and relationships with respect to the scenarios. Currently, the exact definitions and new roles of actors are still under discussion in the project, specifically in WP6.

Ancillary service markets: centralized, distributed or decentralized market approaches for ancillary service provision are discussed in the Smart Net project 19). Five basic coordination schemes for TSO - DSO coordination are discussed in D1.3 of the Smart Net Project.

For primary frequency control, two schemes proposed by Smart Net project (see A.3) are applicable for Sf_A if such markets will be set up in the future; while for the secondary and tertiary frequency control more architectures are needed.

Relevance for Sf_A: while the major focus for Sf_A is the transmission network and its flexibility options including bulk storage and HVDC, it will be necessary to integrate the DER with other DSO resources in the scenario with little inertia. As less reserves can be provided by hydro power, it is vital to solve the reserve issue. Therefore, it is important to collocate these players in the optimal way inside the market (if exists).

The central ancillary service market may be the best option at the beginning, so that the procurement and activation of reserve do not create too much trouble in the distribution grids. Additional constraints should be added with time when more resources join the ancillary service market.

2.2.1.3 Consequent ICT requirements

In D1.3, many variants of scenarios are taken into consideration. In this section, we discuss possible additional requirements and reasons for preferring one variant to another, considering electric system stability and implementation considerations.

Of the 10 possible variants present in chapter 3 of D1.3, we jointly discuss 3 groups to reduce the complexity of the analysis. To do so, we ignore the TSO/DSO distinction, and the difference between Inertial and Primary control mechanisms (as their services in Sf_A are very similar for the involved converters). The remaining three groups are:

Inertial and Primary Control, TSO and DSO, Distributed

Inertial and Primary Control, TSO and DSO, Decentralized

Secondary Control, TSO and DSO, Centralized structure

This section will discuss the first two items together, and then the last one.

Inertial and Primary Control (Distributed and Decentralized)

In the case of primary control, the service consists of sensing the frequency and delivering a power response proportional to the frequency deviation. By contrast, in the case of inertial control, it is proportional to the derivative of frequency.

In fact, if a converter-based resource performs inertia and primary emulation it will use local measurements of voltage and possibly current data. When controlling active power, some form of storage is necessary. In this basic layout, NO data needs to be communicated, as the voltage levels and frequency values are measured locally.

In case there is a need of coordination in the Distributed Control, the units will communicate with the EMS and DMS. The architecture will depend primarily on the power system organization (decentralized and distributed) and consequently on the gravity and solution to future system dynamics.

Secondly, if there would be a market for such service, a certain degree of communication with the EMS and DMS is required. If such market is established, biddings need to be gathered and communicated, and results need to be fed back to single resources to activate reserves. Currently the participation of generators in primary frequency control is compulsory. The DSO and TSO should be able to order eventual corrective actions. Shared databases between DSO and TSO to issue security or operative orders should be needed. Considering the high number of control points, the amount of data is very large.

Currently, the market structure has not been set up; therefore, the requirement for such communications links cannot be clearly specified at this stage. They will be discussed in the later deliverables, when the RESERVE project approach has been fully clarified for all scenarios and variants.

Secondary control

In the Sf_A scenario, the secondary control will remain centralized, yet it needs to be upgraded. The control orders will be issued to the various involved resources. More requirements are needed in the distribution grid where most of the new devices will be located.

2.2.1.4 Summary of RESERVE use case for the Sf_A

For Sf_A the theoretical study is done in WP2. The D2.1 and D2.2 point out the major phase of the research and make use of simulations and HIL experimentations with PMUs. D2.1 points the definition of frequency in the future power system, and D2.2 studies the provision of new frequency controls techniques. The validation trials will be held with data and use WAMS of Romanian System which will provide data to analyse the RoCof and help studying the PMUs standardization process.

On the other hand the roles of DSO and other actors will be clarified via large scale simulation in the Pan European lab Infrastructure composed by real time simulation infrastructures at four of the project partners (UPB, POLITO,RWTH,WIT). For more information, the reader can refer to the D4.1. The Romanian transmission grid will be simulated to define new roles (also with help of WP6), minimum inertia into the grid, new dynamic security assessment of the grid and the form of distributed controls. The Pan European infrastructure is also connected HIL to a base station with 5G capabilities (D4.5 for more information) for the study of new ICT needs in the future power systems. In RWTH HiL connection with power converters can be useful to validate further the results.

2.2.2 Sf_B: Only Synthetic Inertia Scenario

Description in detail of this scenario is in chapter 3 of D1.2 and chapter 3 of D1.3.

2.2.2.1 Basic description of new components and functions

Sf_B assumptions are more futuristic and envisions an extreme scenario. In Sf_B, converter has completely replaced the synchronous generator, hence only converter-based generation (PV and Wind power plants) and consumption exist in the system.

As no more Mechanical Inertia is present in the grid, the frequency does not naturally change following some power disturbance. The frequency is decided by converters' controllers which work in parallel. In this sense frequency become an artificial signal and its definition and use should be redefined. Some introduction on how to operate converters in parallel can be found in A.2.

The Linear Swing Dynamics (LSD) is developed at RWTH to stabilize the system in the Sf_B scenario. As the technique is still under development, an exhaustive description of it will be formulated in later deliverables (D1.5 and D2.3). The basic idea is that without the highly non-linear dynamics of the synchronous generator which is governed by the Swing Equation, the system can have simpler and more controllable dynamics. There is no need to mimic the classical representation of the SGs in converters control (like in Sf_A). The system could be controlled by using linearized swing dynamics for frequency. The global system will be linear, thus a lot of stability problems (such as large or small perturbation equilibrium) could be easily solved.

Starting from a single converter control, the study will extend to a multi-converters layout, for distribution systems and eventually for transmission systems. The Sf_B scenario will consider also the interaction with DC grids, HVDC and will analyse better distribution grid resources and roles of aggregator.

The normal control loops for inertial, primary and secondary control could be adopted, but could also be subject to revision, depending on the definition of stability of the system. The choice lies in the structure of the power systems, i.e. Decentralized or Distributed.

It is assumed that the dynamics from a global level will be similar to that of Sf_A (even if dynamics are of fundamentally different nature), but somewhat faster, requiring slightly more control with shorter time frames (see D1.3). Roles and other major requirements are very similar to Sf_A.

2.2.2.2 Actors and their new role

Roles and new actors will be much similar to Sf_A. Renewable generation, DER and prosumers will be the resources to guaranty the system stability; therefore, more attention should be put into these actors. HVDC lines connecting to AC systems or Offshore Wind power plant need to be taken into consideration as well.

The DSO operation in the Sf_B will be more crucial than that in SF_A in terms of managing the grid stability; therefore, it could have major roles, but the TSO-DSO coordination will be especially needed and ancillary services market structures similar to the ones developed in the Smart net project could be adopted.

2.2.2.3 Consequent ICT requirements

The ICT requirement for SF_B is similar to that for the Sf_A. Information to be communicated and the needed rate will ultimately depend on the grid and market architecture (if exist). In the distribution grids, as much more assets need to be controlled and coordinated, thus they should be able to communicate bilaterally.

2.2.2.4 Summary of RESERVE use case for the Sf_B

In Sf_B, the theoretical foundation is given by the research of defining the principles of the Linear Swing Dynamics (D2.3). This will be done by simulating the stability under different situations (Local, Transient and Global Stability). Proper scenarios will then be constructed to validate the principles on the Pan European Lab infrastructure. Additionally, HiL experiments will be conducted using a converter (D5.1).

3. Use cases for voltage control

With the increasing of penetration of renewable generation up to 100% into the grids, both the transmission and distribution grids would experience difficulties in terms of controlling the system voltage. However, due to the local nature of the voltage, the issue related with voltage control would be more evident in the distribution systems.

3.1 Change towards the futuristic distribution systems

In the distribution grids, the system is expected to be dominated by 100% renewable resources and most of the households and small-scaled industries have their own renewable resources and grid-connected converters. The system dynamics will be much influenced by all the new generation and consumption technologies, which will make use of converters to interface the main grid. Based on the system changes and relevant issues the system may experience (see A.1.2), the following two scenarios are envisioned to solve the voltage problems in terms of dynamics and statics.

- Sv_A: Dynamic voltage stability which aims to reflect dynamic issues in the low-voltage distribution grid, especially the transients, harmonics and stabilities of the voltage under load and local generation changes (readers are advised to read D1.3 section 2.3.1, section 7.2.1; D3.1 chapter 2; D3.2 chapter 2 for more details of this scenario).
- Sv_B: Active voltage management which targets the steady state voltage in the distribution grid in terms of maintaining the voltage within acceptable operational limits (readers are advised to read D1.3 section 2.3.2, secion 7.2.2; D3.1 chapter 3; for more details of this scenario).

3.2 Scenarios design corresponding to the changes

In order not to repeat what have been presented in other deliverables, the description of the scenarios designs are omitted here. The construction of the scenarios through SGAM can be found in the annex of D1.2 and D1.3.

3.2.1 Sv_A: DSO, dynamic voltage stability monitoring

3.2.1.1 Basic description of new components and functions

Currently, voltage dynamics are not a key control task of the system operator, especially at the low-voltage distribution system level. The inverters accompanied with renewable generators are typically configured to track and operate around the maximum point of power, thus behaves like constant power sources. On the other hand, the DC load at the end-user premises behind the rectifiers makes it behave like a constant power load. Therefore, the constant power sources and loads will attribute to the instability of the system voltage due to their natural negative resistance of destabilizing.

Hence, in the future low-voltage grids, the current way of running the distributed renewable generation is no longer viable and they must be controlled in a way that no dynamic instabilities will happen.

The voltage, compared with the frequency, is a local feature. The voltage problem, thus, should naturally be treated locally. Yet, they cannot be solved at each connecting point in the low-voltage grid individually due to the complexity of dynamic controllability of the power electronics. If not somehow coordinated, oscillation and harmonics can be observed. Therefore, **a new function of coordinating the converters' response and actions against voltage instability** issue should be created.

In addition, to be able to respond to the coordinated control of the system, the convertors must be able to **communicate bi-directionally** with the coordinator promptly.

Further, the coordinator would also need other static information, such as locations, property owners, etc. of the convertors to better perform the coordination. Therefore, the **function of managing and static information storage** is also needed.

3.2.1.2 Actors and their new role

Before discussing the roles of actors, we would like to remind the reader again that the discussion is only tentative to complete the picture of the scenario. Therefore, they are subject to changes as the project proceeds.

It is obvious that **prosumers** will emerge in such scenarios as the renewable generators and inverters are installed in their premises. But the prosumers' roles can be ignored in providing such control response as control decisions are not usually made by the prosumer. Likewise, **storage** may not be important to consider individually for such kind control as they simply provide the sources for converters to adjust.

The coordinator described in section 3.2.1.1 is then best done by a local entity, such as an **aggregator** or a **physical equipment,** managing a reasonable number of investors.

The aggregator can be a physical one or a commercial one, depends on the implementation design.

If such services are acquired through a market mechanism, then a commercial aggregator would be more applicable. Its role in such a case is to participate the **local ancillary service market** on behalf of the prosumers, if the voltage control service can be separate and implemented at the distribution level. The local ancillary service market is then in charge of selecting the convertors and maybe associated capacities for providing such kind of services.

Otherwise, the physical aggregator would be a better choice, who in this case gets requirement from the DSO (or an employed service provider) or from the regulation and coordinates the inverters directly. However, such kind of services can also be automatically achieved by physical equipment.

Even though the market approach may be applied in such a case, it would not be seen in a near future as the dynamic support usually requires a fast response.

The inverters assumed in this scenario should be able to communicate with the coordinator and flexibly change their settings to respond the needs of the system in terms of stability. Therefore, it provides new requirement for the **next generation of inverters**.

In addition, intensive communication among different actors in the system also gives opportunities to new ICT technologies and communication service providers to thrive.

3.2.1.3 ICT structures for the new actors

In the case of market implementation, the communication channels are depicted as in Figure 2.

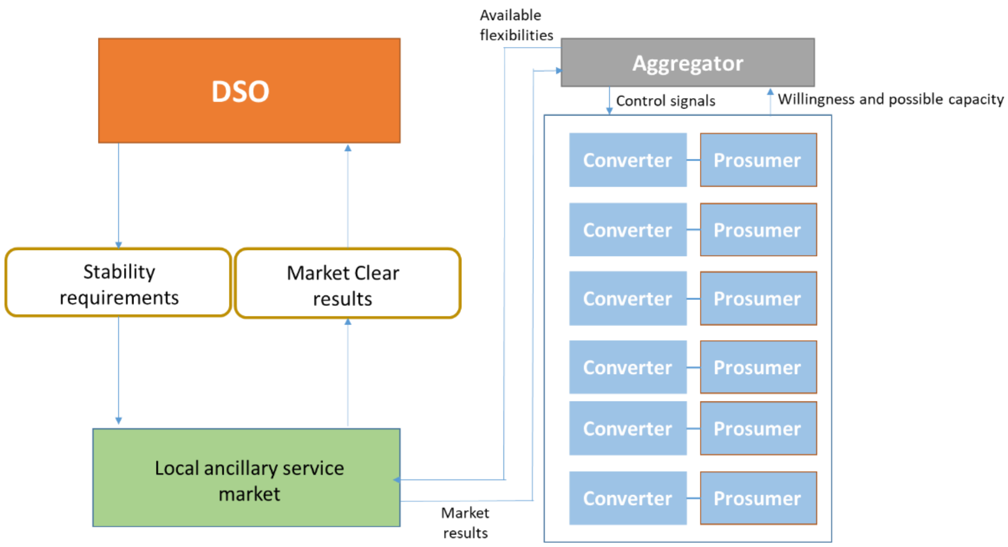


Figure 2 Communication links for the market implementation of dynamic voltage service

The DSO, from the SCADA/DMS system, evaluates the needs for the stability and associated flexibility that should be purchased in the market. Then it transfers such information to the local ancillary service market, which could be an entity or an embedded function within DSO. Such information is also published to the aggregators who would further use it to form their strategy to put the available flexibility into the market. Each aggregator would also communicate with converters/prosumers to obtain their willingness and available capacities to participate the dynamic voltage ancillary services.

After the market clearing, the results are communicated with the DSO and relevant aggregators, who will use the market results to form control strategies when necessary.

Currently, such kind of market has not been setup; therefore, the requirement for such communications links are not possible to be specified at this stage. They will be discussed in the later deliverables if such scheme is adopted by the RESERVE project.

By contrast, in the case of implementing through regulation or network code, the communication channels can be shown as in Figure 3.

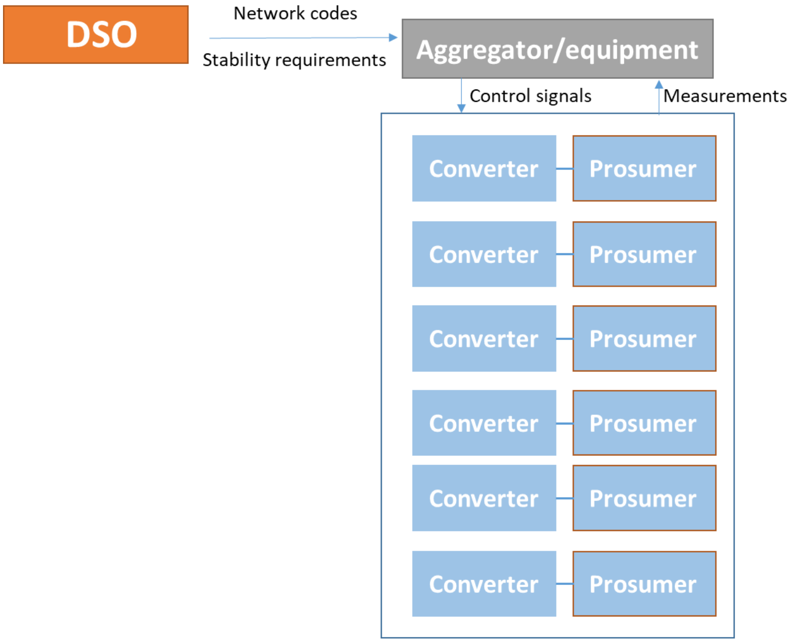


Figure 3 Communication links for regulation driven dynamic voltage service

In the case of implementation through regulation, the aggregator get stability requirements from the DSO or follows relevant network codes to control the network voltage. Therefore, the communication links would be mainly required between aggregators and each convertor. The aggregator takes measurements from each convertor and evaluates the control needs. If it is needed, control signals will be send back to relevant convertors. For specific ICT requirement of such scheme, readers are advised to read D1.3 section 3.2.1.

3.2.1.4 Summary of RESERVE use case for the Sv_A

In the RESERVE project, the use case is defined over the regulation-based scheme where market layers are not required. The coordination role has been assigned to a physical equipment installed in the secondary substation with an enhanced function to calculate the stabilizing control routine. In contrast, each inverter is required to embed several functions to respond to the request from the substation, e.g. wideband system identification, virtual output impedance controller. For more details, readers are advised to read D3.1 chapter 2 and D3.2 chapter 2 for the algorithms, D1.2 section 4.1.2 for the system requirement and D1.3 section 3.2.1 for the ICT architectures, requirements, etc.

In order to prove the concept that has been developed in WP3, a series of field trials will also be arranged. D5.1 describes the trials of the voltage concept in Ireland and the validation of initial network codes and ancillary service definitions.

3.2.2 Sv_B: DSO, Active voltage management

3.2.2.1 Basic description of new components and functions

From the steady-state operation point of view, the first concern of the DSO for the low-voltage distribution grid is that the voltage must be within acceptable limits. Therefore, in the grids with proliferated power electronics, the static voltage management should **harmonize other control methods** with the control of the inverters installed at the users.

The difficulty for such control is that it needs to guarantee the voltage of all connecting points from the MV (usually has higher voltage to ensure all the LV users has acceptable voltage) to LV (usually the far distant user at the end of the feeder has significant voltage drop under high demand period) are within the limits. Thus, the calculation burden is tremendous and impossible for online application. The historical power profiles of customers then are expected to be used to form the strategy off-line, which will be used online later as a guidance for the voltage control. Consequently, equipment or tools for **data acquisition, storage and analysis** are needed.

Further, **new static voltage control architecture** is envisioned to control the large amount of connecting points, especially those on the LV feeders which are currently not considered independently. Hierarchical control structure seems suitable for such change. That is a coordinator calculates the target range of the voltage at some points in the network, by considering multiple factors crossing multiple time scales. Then the control range or requirement can be communicated to a lower level surrogate who would further calculate a more precise control point and send them to the next lower level. This process continues until reaching the last level who directly coordinates a few number of customer/prosumers. The number of intermediate level can vary from case to case.

As in the Sv_A scenario, such new architecture also need to be in a coordinated fashion so that the control results will not oscillate and the efficiency of different controllable equipment can be improved as well. In addition, such control should not cause other violations in the system and preferably at the same time increase the efficiency of other key performances of the system, such as decreasing the system losses, etc.

In addition, to be able to respond to the coordinated control of the system, the convertors must be able to **communicate bi-directionally** with the coordinator or its surrogates promptly.

Further, the coordinator would also need other static information, such as locations, property owner, etc., of converters to better perform the coordination. Therefore, the **function of managing and static information storage** is also needed.

3.2.2.2 Actors and their new role

Prosumers are assumed in such scenarios as the renewable generators and inverters are installed in their premises. Like in the Sv_A, the prosumers' roles can also be ignored in the active voltage management as control decisions are not explicitly made by the prosumer.

The top-level coordinator described in section 3.2.2.1 is best to be the DSO who holds all information of the grid, while the surrogates can be a local entity, such as an **aggregator** or a **physical equipment,** managing a reasonable number of investors.

The aggregator can be a physical one or a commercial one, depending on the implementation schemes.

The same as in the Sv_A, if such the services are acquired through a market mechanism, then a commercial aggregator would be more applicable. Its role in such case is to participate the **local ancillary service market** on behalf of the prosumers, if such market will be setup. The local ancillary service market is then in charge of selecting the convertors and maybe associated capacities for providing such kind of services.

Otherwise, the physical aggregator would be a better choice, who in this case gets requirement from DSO (or the service provider the DSO employed) or follows the regulation and coordinates the inverters directly. Such kind of services can also be automatically achieved by physical equipment through enhanced software or embedded function.

The market approach seems preferable in such case as the control requirement would not expect to be changed very frequently. However, it would take a long time to implement such market as currently the ancillary services markets do not trade voltage support in most of the countries.

Therefore, maybe the acquisition of such support driven by regulation is more likely in the near future.

The inverters assumed in these scenarios should be able to communicate with the coordinator or at least the surrogates and flexibly change their settings to respond the needs of the system. Therefore, it provides new requirement for the **next generation of inverters**.

In addition, intensive communication among different actors in the system also gives opportunities of new ICT technologies and **communication service providers**.

3.2.2.3 ICT structures for the new actors

In the case of market implementation, the communication channels are depicted as in Figure 4.

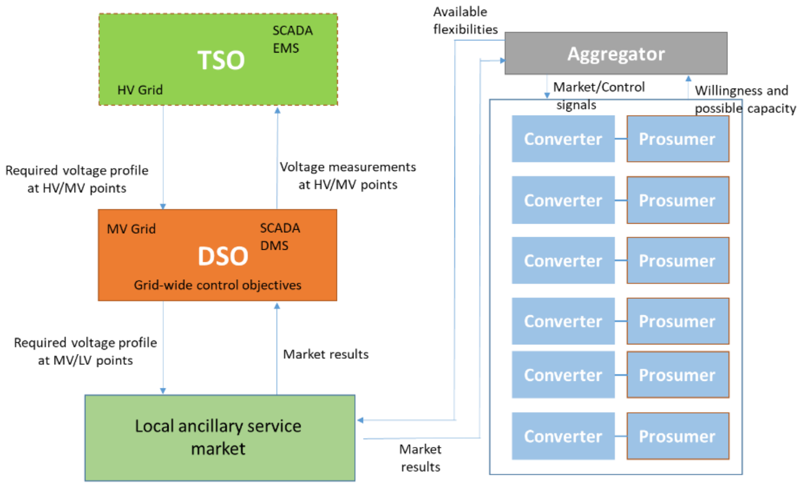


Figure 4 Communication links for the market implementation of static voltage service

In the hierarchical control structure, the TSO decides the required voltage profile at all the high voltage nodes according to its own objectives and information of the high voltage transmission network. The required voltage profile will be then communicated with the relevant DSOs. Currently, the voltage profile is regulated by grid codes (refer to annex 6.3 of D3.2 for details).

For the DSO, from the SCADA/DMS system and the historical power profiles of the customers in its grid, it evaluates the required voltage profiles at the MV/LV points by considering different control objectives, such as minimising system negative sequence and losses, etc. The requirement will be sent to the local ancillary service market, which could be an entity or an embedded function within the DSO. Such information is also published to the aggregators who would further use it to form their strategy to put the available flexibility into the market. Each aggregator would also communicate with the converters/prosumers to obtain their willingness and available capacities to participate the ancillary services for voltage.

After the market clearing, the results are communicated with the DSO and relevant aggregator, who will use the market results to form control strategies when necessary.

Currently, such kind of market has not been setup; therefore, the requirement for such communications links are not possible to be specified at this stage. They will be discussed in the later deliverables if such a scheme is adopted by the RESERVE project.

By contrast, in the case of implementing through regulation or network code, the communications channels can be shown as in Figure 5.

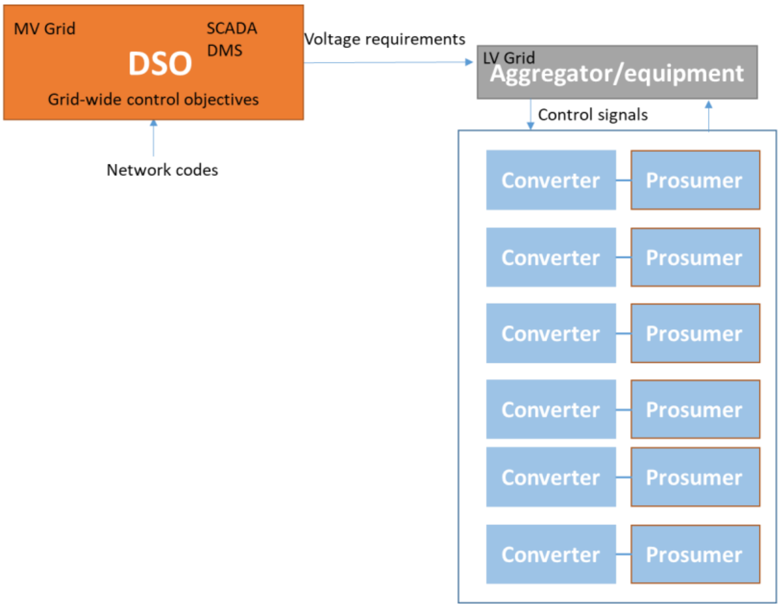


Figure 5 Communication links for regulation driven static voltage service

In the case of implementation through regulation, the aggregator gets voltage profile requirements from the DSO (or the service provider employed by DSO) to control the network voltage. Therefore, the communication links would be mainly required between the aggregators and each convertor. The aggregator takes measurements from each convertor and evaluates the corrective actions. If it is needed, control signals will be send back to relevant convertors. For specific ICT requirements of such scheme, readers are advised to read D1.3 section 3.2.2.

3.2.2.4 Summary of RESERVE use case for the Sv_B

In the RESERVE project, the use case is defined over the regulation based scheme where market layers are not required. The top coordination role has been assigned to the DSO and the surrogate roles are given to physical equipment installed in the secondary substation. Each inverter is required to have communications links with the surrogate and maybe even with the top coordinator. In addition, the inverter also needs to be able to operate in different configurations from current settings point for today's network codes.

For more details, readers are advised to read D3.1 chapter 3 and D3.2 chapter 3 for the algorithms, D1.2 section 4.1.3 for the system requirement and D1.3 section 3.2.2 for the ICT architectures, requirements, etc.

In order to prove the concept that has been developed in WP3, a series of field trials will also be arranged. D5.1 describes the trials of the voltage concept in Ireland and the validation of initial network codes and ancillary service definitions.

4. Conclusion

This deliverable describes the energy system changes in the future with special focus on the aspects of frequency and voltage. For example, for the transmission grids there will be an increase of Bulk Storage systems and Inertia will fall eventually to 0 in one of the RESERVE scenarios. In contrast, for the distribution grids, the structure of the system is expected to be dominated by 100% renewable resources and most of the households and small-scaled industries have their own renewable resources and grid-connected converters. The system dynamics will be much influenced by all the new generation and consumption technologies.

Issues caused by these changes are also discussed in this deliverable. Firstly, new requirements and needed functions are introduced with respect to solving the issues in the new scenarios. Emerging actors or roles to take case of these new functions are briefly described. Corresponding ICT structures among actors by considering two different implementation schemes (i.e. market based mechanism and regulation based mechanism) are introduced.

In order not to repeat what other deliverables has documented for the use cases developed in the RESERVE project, we give references of different deliverables to various aspects of the use cases.

Based on detailed background of the role of converters, which is the real revolution in the grid both for *Sf_A, mechanical-synthetic inertia scenario* and especially for *Sf_B, only synthetic inertia scenario*, we present 3 types of energy system organization: decentralized, centralized and distributed. We discuss relevant ICT and implementation requirements (considering a competitive market for the frequency reserves, if such market will exist in the future). The new ICT will be needed more in the distribution systems in Sf_B with respect to Sf_A. Moreover, a large part of the communication needs depends not only on the technical provision but also on the implementation schemes. By contrast, the decentralized systems have less and simpler ICT needs. In the future, more extreme dynamics will force the system to adopt a more complex distributed system. A clear definition of the roles and actors is needed to understand the best architecture for frequency control. Proper KPIs, narratives and preliminary results on how to reach these goals will be discussed in D1.5 as work in other WPs advances.

For the voltage scenarios, there are two fundamental implementation schemes, i.e. market-based mechanism and regulation based scheme (network codes).

The dynamic voltage control scheme Sv_A requires fast responds from the involved inverters; therefore, the market solutions may not be feasible in the phase of online control. It may only be useful to select the participating inverters based on the forecasted system needs. On the contrary, the regulation based implementation can provide a quicker solution for the dynamics. However, it automatically involves all relevant inverters, most probably even without the option out for the inverters. The market-based solution needs to involve more actors. It is necessary to provide regulations and rules for the operation of the markets, as well as ICT layers to enable it. While the network codes based realization needs less involvement of actors and ICT structures. Both solutions propose a great demand for the communications links among the physical inverters with their controllers or up level coordinators.

The active voltage management scheme Sv_B requires mid-term optimal steady state operation of the network. The control strategies need to be harmonized with the existing practices; therefore, it can also be used in the transition towards the 100% RES. Due to the large calculation burden and control targets, it may not be able to use online optimization for the system-wide scale. Therefore, the hierarchical structure may be helpful to ease the control by using historical data to derive the target for each point where a surrogate locates. The surrogates then further calculate the control needs under their control, in such a way that the final results fit into the control targets sent by the higher-level controllers. The market solution is suitable to this scenario as it requires long-term and economic operation of the system. Similarly, more actors will be involved so as the ICT structures. In contrast, the regulation based implementation would be simpler, but may not be easy to design an economic framework for the service providers.

Thus, the regulation (network codes) based implementation schemes may be more applicable in the near future. The RESERVE project is then dedicated to proposing new network codes or relevant modifications so that the voltage issues of the grid when facing 100% renewable can be resolved.

We would like to emphasize again that the actors and their relevant roles discussed in this deliverable are initial proposals from WP 1 which may be subject to change following further discussion in the project as a whole.

5. References

1) Vidyanandan, K. V., and Nilanjan Senroy. "Primary frequency regulation by deloaded wind turbines using variable droop." *IEEE transactions on Power Systems* 28.2 (2013): 837-846.

2) Dreidy, Mohammad, H. Mokhlis, and Saad Mekhilef. "Inertia response and frequency control techniques for renewable energy sources: A review." *Renewable and Sustainable Energy Reviews* 69 (2017): 144-155.

3) Zhong, Qing-Chang, and Tomas Hornik. Control of power inverters in renewable energy and smart grid integration. Vol. 97. John Wiley & Sons, 2012.

4) H.Bevrani, T.Ise, Y.Miura. Virtual synchronous generators: A survey and new persepctives. Electrical Power and Energy Systems. 13 July 2012

5) Review of Power Sharing Control Strategies for Islanding Operation of AC Microgrids. Han, Hua; Hou, Xiaochao; Yang, Jian; Wu, Jifa; Su, Mei; Guerrero,Josep M. IEEE Transaction on Smart Grids.

6) B. Shoeiby ; D. G. Holmes ; B. P. McGrath ; R. Davoodnezhad. Dynamics of droop-controlled microgrids with unequal droop response times. Australasian Universities Power Engineering Conference, AUPEC 2013, Hobart, TAS, Australia, 29 September - 3 October 2013

7) CEN/CENELEC/ETSI Joint Working Group on Standards for Smart Grids .CEN-CENELEC-ETSI Smart Grid Coordination Group: Smart Grid Information Security. 2012

8) P1 – Policy 1: Load-Frequency Control and Performance. A1- Appendix. 2013. ENTSO-E.

9) Trends in Microgrid Control. IEEE-PES Task Force on Microgrid Control. Chairman: Claudio A. Cañizares Secretary: Rodrigo Palma-Behnke. IEEE TRANSACTIONS ON SMART GRID, VOL. 5, NO. 4, JULY 2014 1905

10) Guerrero, J. M., Vasquez, J. C., Matas, J., De Vicuña, L. G., & Castilla, M. (2011). Hierarchical control of droop-controlled AC and DC microgrids—A general approach toward standardization. *IEEE Transactions on Industrial Electronics*, *58*(1), 158-172.

11) Stability, Control, and Power Flow in Ad Hoc DC Microgrids. Wardah Inam, Julia A. Belk, Konstantin Turitsyn, David J. Perreault. 2016 IEEE Workshop on Control and Modeling for Power Electronics (COMPEL ' 16).

12) Union for the Coordination of Transmission of Electricity, Operation Handbook Appendix 1 -

13) Load-Frequency Control and Performance. Paris: ENTSO-E/UCTE, www. entsoe.eu.

14) ENTSO-E Commission Regulation (EU) 2016/631, "establishing network code on requirements for grid connection of generators," 14 April 2016.

15) ENTSO-E Commission Regulation (EU) 2016/1447, "establishing network code on requirements for grid connection of high voltage direct current systems and direct current-connected power park modules," 26 August 2016.

16) ENTSO-E. Network Code on Load Frequency and Reserves. 2013.

17) ENTSO-E. OPERATIONAL RESERVE AD HOC TEAM REPORT, 2012

18) ENTSO-E WGAS - SURVEY ON ANCILLARY SERVICES PROCUREMENT, BALANCINGMARKET DESIGN 2016, March 2017

19) https://www.swissgrid.ch/swissgrid/en/home/reliability/WAMS.html put reference in list.

20) http://smartnet-project.eu/

6. List of Abbreviations

AC	Alternate Current
AS	Ancillary Service
DC	Direct current
DER	Distributed Energy Resources
DFIG	Double Fed Induction Generator
DSO	Distribution System Operator
EMS	Energy Management System
ENTSO-E	European Network of Transmission System Operators for Electricity.
EV	Electric Vehicle
ESS	Energy Storage Systems
FCR	Frequency Containment
HiL	Hardware in the Loop
HVDC	High Voltage Direct Current
KPI	Key Performance Indicators
PMU	Phasor Measurement Unit
POLITO	Politecnico di Torino
RES	Renewable Energy System
RWTH	Rheinisch-Westfälische Technische Hochschule
SG	Synchronous Generator
TSO	Transmission System Operator
UPS	uninterruptible power supply
WAMS	Wide Area Measurement System
UPB	University Politehnica of Bucarest
WIT	Waterford Institute of Technology
WP	Work Package

List of Figures

A.1 System changes

A.1.1 System changes from the frequency perspective

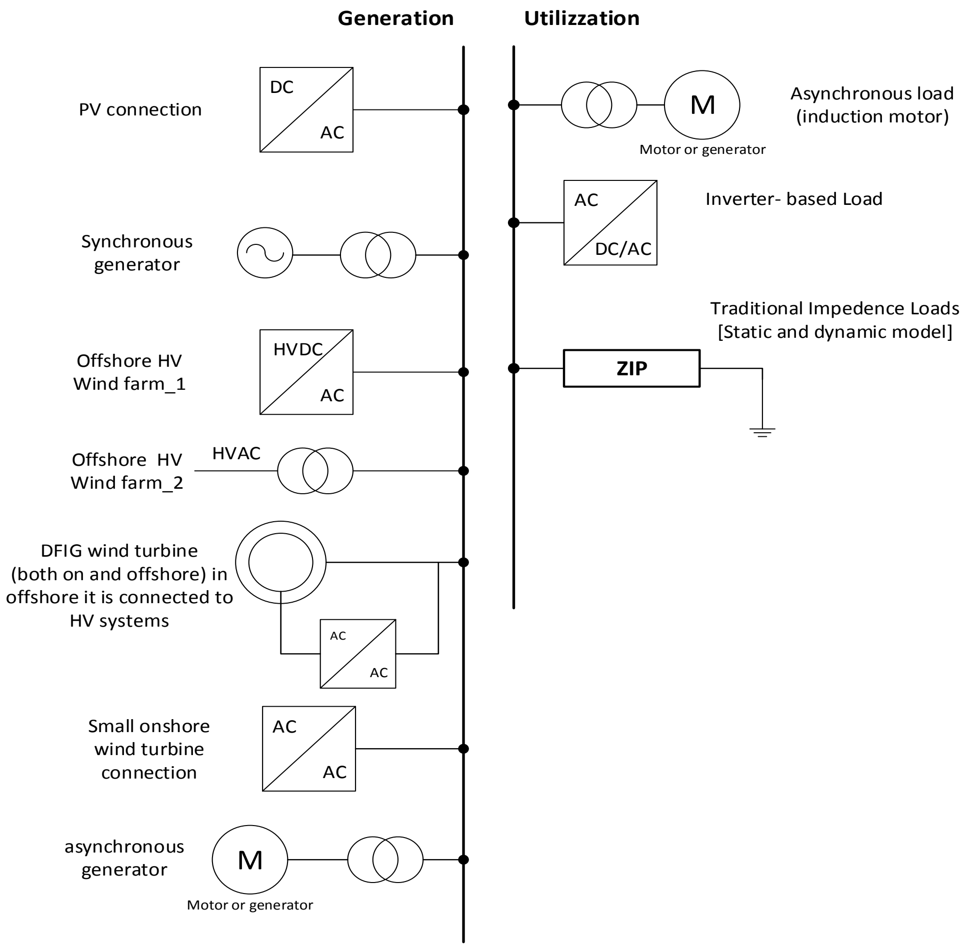


Figure 6. Generation and user grid connection layout for AC grid System

Bulk generation, distributed energy resources (DER) and loads in the electric grid can be connected to the grid through various means. This is important as the connection layout defines the possibility to control active power, reactive power, voltages and current fed to the grid. Same components can sometimes have different connection layouts. In general, for generation (considering Bulk generation of big traditional plant and DER) and utilization, main categories we recognize are:

For Generation

Converter-based connections: In particular Photovoltaic Power produces DC electric current and needs a converter to operate in the AC power system. On the other hand, wind turbines produce electricity through the use of electrical rotating machines, but for maximizing the produced power, they need to change velocity quite often, following the wind speed. For this reason, AC-AC converters are used to allow a big speed variability and are still able to produce electricity at the grid frequency both at the onshore and offshore level considering also distinctions between Double Fed Induction Generator (DFIG) and permanent magnet generator. In the case of offshore wind parks, the connection with the AC main grid is assured through the use of High Voltage Direct Current (HVDC) links.

Synchronous generators connect mainly bulk generation (coal, hydro, nuclear, gas based) to the grid through the use of a transformer. It connects also particular forms of renewables sources like geothermal and thermal solar plants (which may be present in negligible quantities compared to PV and Wind turbines)

For Utilization

- **Asynchronous generators** or induction motors are representative of the usual industrial load
- **Converters** are used to connect DC loads and precisely control the torque and velocity of AC electrical motors. In the future, more and more appliances will be of DC nature and thus need a transformation of the electricity vector before being used. New users of the grid connected through converters are Electric Vehicle charging stations (EVs) and prosumers.
- **Traditional Impedance** which is used to represent the classical consumer load. It is usually modelled by static or dynamic models and does not present any converter Interface (for more complex representations, ZIP models are used). Usually traditional loads (like lamps) in the past did not suffer greatly from small frequency or voltage variations and where direclty attached to the grid.

In a very broad sense we can say that presently all these categories are represented into the grid. In the future a lot more of converter connected generation and utilization is expected to be connected into the grid thanks to the great expansion of PV sources and in distribution grid converter based resources can reach up to 100%.

Without entering too much in the well-known issues for frequency control caused by the increasing of renewable converter based generator into the electric grid, we refer directly to the specific Deliverables of the RESERVE project, where these issues are treated in detail and the reader can learn about these problems from different points of view. In particular, the reader can refer to:

Deliverable 1.1: Chapter 4, section 4.1, 4.2, 4.3, which define and describe what is the frequency stability in modern power systems, what and how does the current architecture for frequency of control work, what is Inertia and Virtual Inertia and what are the measures to improve stability into the grid from a general point of view.

Deliverable 1.2: Chapter 2. The challenges of high RES system (up to 100%) are listed and referred to the two frequency scenarios of project devised. The lack of inertia and the high variability of renewable sources are the major reasons for concern from the Frequency control point of view.

Deliverable 2.1: Chapter 2 shows how frequency is not constant at steady state and moreover it is not unique in the grid, but differences between nodes appears even under steady state conditions and more during transients. Since the converters are “frequency takers” and do not impose their frequency values into the grid, the continued decrease of synchronous generators which instead impose the frequency at their corresponding nodes, will make frequency deviation between the nodes higher and potentially dangerous.

Deliverable 2.2: In Appendix B the frequency issues caused by the variability of PV and Wind power production from the Romanian power grid perspective are presented.

A.1.2 System changes from the voltage perspective

The resources connected to today’s distribution system grid (medium to low voltage grids, mostly from 35kV to 400V voltage level grids) do not provide ancillary services. In the future distribution grids, the structure of the system is expected to be dominated by 100% renewable resources and most of the households and small-scaled industries have their own renewable resources and grid-connected converters.

Consequently, the traditional end-point electricity customers become prosumers with increasing DC load at their premises, be the LED-based illumination, brushless DC motors and permanent magnetic synchronous motors based rotating apparatus, electric vehicles, etc.

Of course, as legacy, the traditional AC loads may not disappear, especially those who benefits from AC driven technologies. Therefore, the futuristic distribution systems at the low-voltage level would be a combination of the both AC and DC loads at the end-point user level.

To continuously utilize the transmission and distribution network assets which values hugely, especially the infrastructure, AC grids would still be the most majority, even though DC transmission and distribution technology will be witnessed increasing.

Micro-grids, as another solution of maximal exploration of local renewable resources to balance the demand without loss the capability of connectivity to the distribution grids, will also be envisioned to increase in the future.

A.1.2.1 Issues in the electrical part

Currently, the distribution system is overwhelmed by loads without an ability to participate the control of the system, both in terms of frequency and voltage, not to mention the active participation of the dynamic control. Therefore, the control of the voltage in the grids is usually done by using on-load tap changing transformers in the substation, transformers, capacitor banks, series reactors, static Var compensators, static synchronous compensators, etc.

The passive load then exhibits the characteristic mixed features which can be modelled by static polynomial ZIP model, i.e. a combination of a constant impedance load (Z) which the power dependence on voltage is quadratic, a constant current load (I) which is linear with respect to the voltage change, and a constant power load (P) independent of changes in voltage. Therefore, it is clear that the voltage changes in the distribution network will cause changes in the load part instantaneously. Especially for the constant power load, changes of load switching event or voltage decreasing event can cause increase of the withdrawn current from the grid, which further deteriorates the voltage condition in terms of system voltage stability.

Moreover, the allowance of large number renewable generation connection to the distribution grids, especially behind inverters, will also cause dynamic stability issues in the grids as their changes of operation condition or set-point can be very fast.

In addition, with the proliferation of the converter-based grid connection, un-controlled and un-coordinated inverter and rectifier behaviours and interactions with other system components will also introduce unwanted physical effects to the grids, such as oscillations and harmonics.

The above mentioned voltage related problem will be presented in the future system mainly in terms of dynamic stability, i.e. affecting the system stability in very short time (e.g. a couple of ms to seconds) (D3.1 chapter 2 and D3.2 chapter 2 are recommended for details).

In addition to that, there will also be issues related with static voltage problem, i.e. affecting the system operation efficiency in a long timeframe (e.g.one day to a year), besides the undervoltage or overvoltage caused by these distributed renewables.

With the ability of controllable converter-based loads, the system operator, mainly DSO can require the active participation of the loads to help addressing the voltage issues in the grid, especially the feeder where they are connected to. Thus, they can be regarded as available resources, together with traditional voltage control resources (on-load tap changing transformers in the substation, transformers, capacitor banks, series reactors, static Var compensators, static synchronous compensators, etc.), to collectively drive optimized system operation conditions in the static operation. The objective of the system can be any one selected by the DSO/TSO, such as minimizing system losses, alleviate feeder congestions, etc.

Even though, traditional voltage management method may, to some extent, still be useful to solve static voltage problem without considering the converter-based loads, the support of reactive power from other resources may cause increased power flow over the feeders in question. This will cause system congestion and greatly decrease the efficiency of the grid operation.

If such huge optional voltage control resources are ignored, it would be a waste to the overall system. What is even worse is that without the cooperation of such large amount of distributed autonomous loads, the static voltage of the a single phase feeders can break the operational requirement (overvoltage or under-voltage), and the system can hardly achieve the expected operation point as the active load behaviours can be completely different from DSO/TSO’s expectation. In addition, the degree of voltage unbalance across the three phases can also increase drastically and violate relevant operational codes (D3.1 chapter 3 and D3.2 chapter 3 are recommended for details).

It should be noted that storage would substantially assist to address the voltage problems through the control of converters to providing leading or lagging current; however, in our scenarios design the control of battery at the end-point customers is ignored because the key is in the control algorithm of the convertor, thus the battery storage simply set the capacity constraints on the control algorithm.

A.1.2.2 Issues in the actors and business part

For current distribution system operators, they manage the distribution grid without many responsibility to provide ancillary services to the control of the system. However, with the development of the 100% renewable energy in the grids, especially with a large number of them in the distribution grids, the DSOs will have to face the problem of managing new devices and information from the network in real-time or DSO will employ a service provider.

From the point of view of system voltage control, they are currently provided by the TSO at the high voltage network. Specifically, TSO would adjust the voltage of buses to which the distribution network is connected by adjusting the set point of adequate generators (say, >10MW), on-load tap changing transformers in the substation, transformers, capacitor banks, series reactors, static Var compensators, static synchronous compensators, etc. Further, the DSO may adjust the tap of the transformers of the primary or secondary substations to provide expected voltage. All these adjustments regarded as mandatory services without remuneration.

However, with the system changes, such kind of services for the voltage control in steady-state operation may not be free any more for the customers or for the service providers, depending on the importance of such services we defined. Such services should be acquired from different levels of markets, dependent on the voltage level and the impacting size of the services. For example, the voltage control at the high voltage bus (at the transmission level) would be required at the transmission ancillary service market; while the voltage control at the distribution level or even the low-voltage feeder level should be required at the local markets, if it is possible to separate them like this.

For the voltage control discussed in this report, i.e. in the distribution system level, the acquisition of the resources can be in two different ways. The first one is through the commercial aggregators, or through the physical aggregators (D1.3 section 2.3).

However, there must be another solution of acquiring the reactive power support for the system voltage, especially for the dynamic voltage control. Because the dynamic voltage stability would require a fast response from the convertors in real-time, there may not have enough time for the market solution. Therefore, network code should be designed for such control, especially in emergency. Of course, in the near future, the network code solution would be expected to appear before the market solution for the reactive power acquisition for voltage problems.

Virtual power plant (D1.3 section 2.1), can also contribute to the system voltage control. However, as the generation resources would be coordinated by an organizer (such as an aggregator or a DSO), the services they provided would be more suitable for static voltage control, i.e. through the market mechanism in either local market or ancillary service market at the transmission level.

A.1.2.3 Issues in the ICT part

As the voltage control will be greatly related to the distribution network in the new changes, there will be many emerging actors and equipment that would need the support of the communication infrastructures.

Therefore, the main issue for the ICT is to provide required communication links and services for the new functions and actors, in terms of qualified bandwidth, latency, jitter, security, data integrity, etc. Especially to provide communication links and services to large amount of equipment to grid is the challenge for the ICT.

In addition, since the business model of the future system is not yet defined it is also difficult for the ICT to pinpoint the blueprint clear roll-outs. In the later section of this report, the ICT requirement and possible architectures that will be developed under the use cases will be discussed.

A.1.3 Network examples

Transmission and distribution systems present a really important difference: the number of control points in future distribution grids will increase drastically, see Table 1; these numbers are not 100% precise but give a first impression to get a feeling of the number of converters involved, compared to transmission grids. Distributed techniques should take care of this enormous amount of units to be connected with suitable technologies and possibly hierarchical systems.

Table 1: Distribution and Transmission Grid examples

Examples	**Grid Characteristics**	**DER**	**Utilization**
Typical Medium Urban Distribution Grid (Torino)	**8** HV / MV substations **3800** MV / LV substations **2100** Kms of MV network extension **3000** Kms of LV network extension		561.000 total customers (which in the future will become converter connected) 690 MV customers 2.950 GWH/anno delivered energy
Typical rural Distribution Grid (Monza) (about 25.000 inhabitants)	**235** nodes **368** branches **9,5** MW peak power (negative) **9** MV feeders	29600 kW DG gross capacity	25.000 inhabitants 9.600 LV customers 43 MV customers

Examples	**BULK generation**	**Transmission Grid**
Typical Small Country (Ireland in 2010)	**2124** MW Wind Capacity **2851** MW Hydro Capacity **2851** MW Thermal Capacity **18** thermal power plants **27** hydropower plants **164** wind power plants	**441** AC Power Lines **247** Stations **550** Sections **683** Nodes **677** Number of Bus bars **514** Number of Two-Windings Transformers **6** Number of Three-Windings Transformers
Typical medium Country (Italy in 2015)	**18.5 GW** Hydro Capacity **8.9 GW** Wind Capacity **20 GW** Sun Capacity **75 GW** Thermal Capacity	**703** Buses **113** traditional big Generators (fossil fuel based)

A.2 The converter role

A.2.1 Converters as virtual synchronous generators (Sf_A)

Nowadays converters are, from the point of view of the electric grid, considered as Controlled Current Sources. Their goal is to inject a certain predefined active power into the grid. This is done by controlling the internal voltage of the DC link which acts like a capacitance (see **Error! Reference source not found.**). The internal capacitance discharges or charges following the injection of power coming from the power source (like a battery, a PV panel, or a wind turbine) and the discharging of power comes from the produced P_{AC}. In this sense a new $I_{AC,ref}$ is injected into the converter controller which consequently regulates its Pulse Width Modulator (PWM) 2). The voltage level and frequency are taken from the grids and reproduced equally by the converter, which behaves like a frequency taker (see D2.1). Reactive power can be determined by adding a reactive component in the reference current.

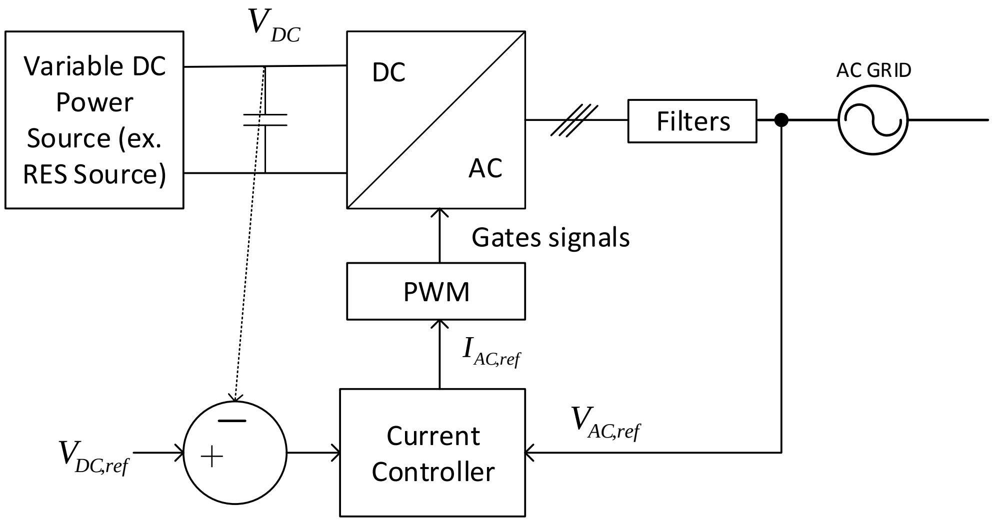


Figure 7: Simple schema of converter control connected to the grid

In the future, converters will be able to deploy frequency control. As a matter of fact from the point of view of the grid, the goal is to model a Synchroverter: a converter which behaves (almost) like a synchronous machine, capable of imposing a certain power and behaving more like a Controlled Voltage Source.

Converter Control Law will try to imitate the dynamics of synchronous generators (inertia and damping property) when deciding the reference voltage and current value for the control 1). The Converter Control Law is mainly used to control DER or a group of flexible resources to behave like a synchronous generator and consequently enter the frequency and voltage control loops. If DERs are in distribution grid, it requires the grid to be connected to the main AC grid. Other control laws can be implemented inside inverter controllers.

In general, the control system tries to emulate inertia, damper effects of the rotor windings of the Synchronous Generators and also provide primary frequency and voltage control. It is completely local and based on local measurements. However, in a more advanced layout, it is possible to perform secondary control loops, given external signals from communication layer.

Big importance should be given to sensors, and to measurement and communication modules of the converter: Remote Terminal Unit and Programmable Logic Controller should be carefully investigated and properly designed. PMU and Micro PMU will be used in the project (both in simulation and in HIL experimentations) and their results will be carefully analysed.

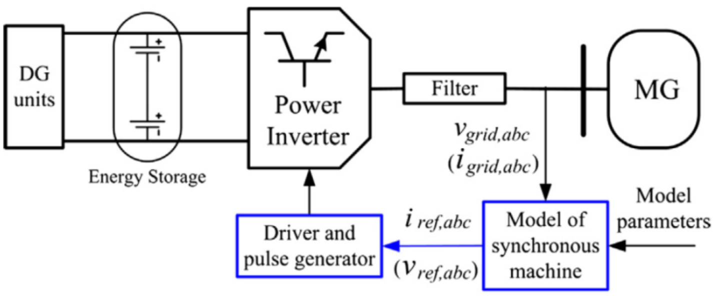


Figure 8: Principal components of Control of a grid-tied converter having virtual synchronous generator characteristics 1)

A.2.2 Parallel operation among converters (Sf_B)

There are two main families of techniques for parallel operation of convertors: Communication based and non-communication (droop) based.

A.2.2.1 Communication based techniques

The most important communication based families are:

- Master/Slave: A master unit will set the voltage level of the principal bus and sends its current to other units; in case of deviation, other slave units will change their output current accordingly. The slaves can also track the voltage of the principal bus to synchronize their voltages. Usually the master will be the highest power rated converter to be able to deal with the transient.
- Concentrated Control **8)**: it is usually used in the UPS. The total load current is measured and transmitted to a central controller. Then, based on each DER unit characteristics, the contribution of each unit is determined and the output current reference set points are sent back to the units; an outer loop simultaneously controls the voltages of the system. This method results in a fast mitigation of transient; however, communication is crucial in this scheme and its failure will lead to a system collapse. Two fundamental communicated signals are needed: current sharing signal and voltage signal (usually used for synchronization with the grid).
- Distributed Controlled: There is no master and no central control, but it still needs communication for sharing current reference and also a signal (that can be local) for synchronization (frequency). But it in general needs less communication bandwidth and moreover it permits plug and play of converters easily (any converter can connect and disconnect from the grid without causing major stability problems).

Some architecture examples and a simple Data Scheme is provided below, which give us an approximately idea of the communication requirements of such systems.

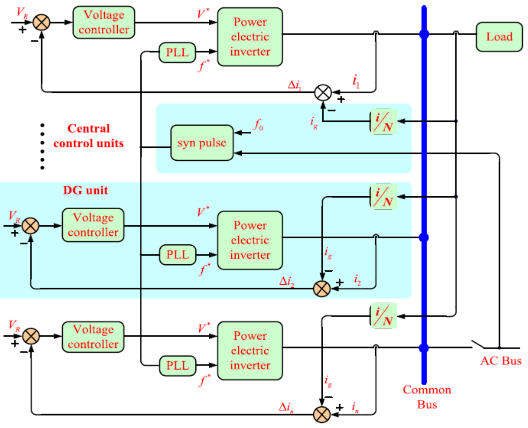


Fig. 1. Control schematic of the concentrated control.

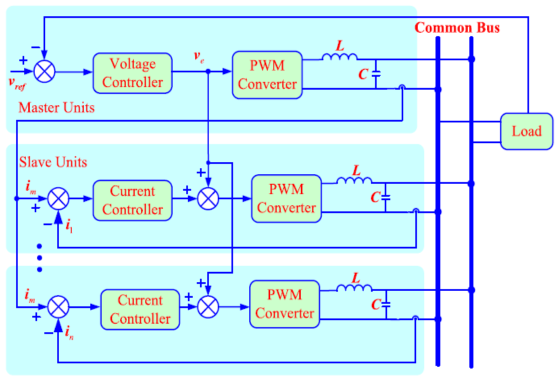


Fig. 2. Control structure of the master/slave control.

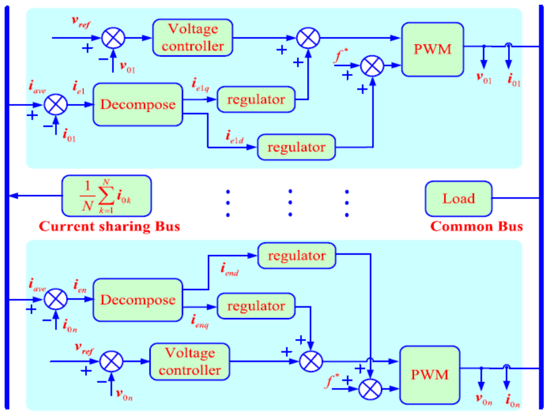


Fig. 3. Control structure of the distributed control.

These Images describe a possible layout for Communication techniques.

These three schemes of control 4), share more or less the same Communication needs. The most important data to be communicated is the current reference signal, so that converters can properly share the load of the Micro-grid.

Figure 9 Converter communication based techniques

Data Scheme:

Data	**Description**	**rate**	**Zones[from SGAM Model]6)**
i_{ref} **[A]**	Current to be shared among converters	As fast as possible	From Process to Operation
$\vec{v}$ **or f* [V, Hz]**	Voltage or frequency level	Less fast, depending on the needs of grid stability.	

A.2.2.2 Non communication based techniques for converter (Droop Based)

Definition: this family of techniques exploits the droop concept in today's regulation control schemes based on changing P and Q production by measuring local frequency and voltage magnitude. On the contrary of synchronous generator case, frequency and voltage will be changed as the consequence of the ΔP and ΔQ sensed by the converter. In this way we minimize the need for communication and we have plug and play feature for the converters. However to improve stability and to assure proper connection with the grid secondary and tertiary control is needed.

Basic layout: In the basic layout there is no need for communication 5) and corresponds to Primary Control. It can be conventional (P-f, Q-v), inverted (P-v, Q-f) or mixed, depending on the nature of lines (Resistance or Impedance based) and presence of Voltage Output Virtual Impedance, but they basically use the same control principle.

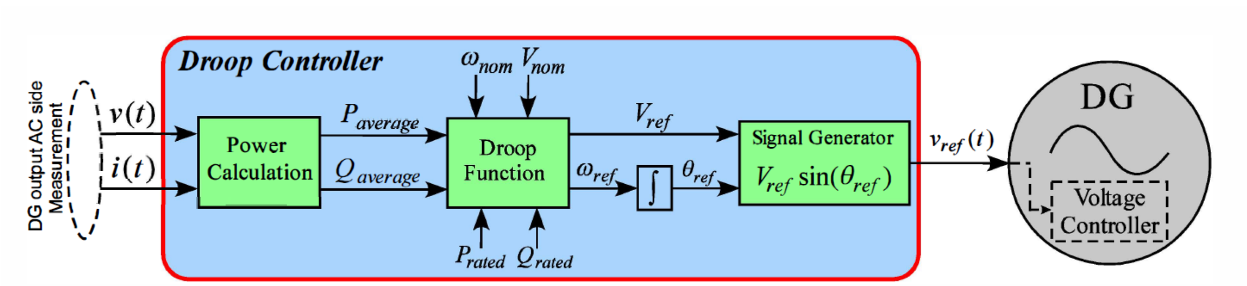
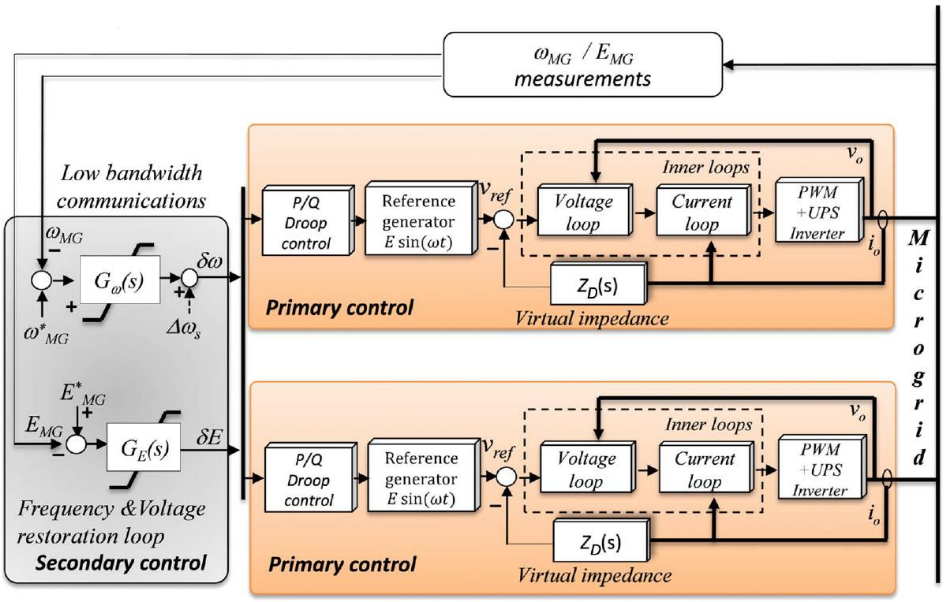


Figure 10: Basic layout of the control of primary droop based control taken from 5).

Advanced layouts: the droop control techniques take into account also secondary and tertiary control hierarchy. In secondary control, two additional signal $\delta\omega$ and δE are sent to some converters (usually the bigger ones) with hypothetically similar or slightly faster rate of today's main grid secondary control unit. Tertiary control will instead sends some signals to the Secondary Controller (reasonably from the TSO operation management system to the DSO management system) about P and Q rated values that the distribution system should produce. Moreover, in case of microgrid, it is also in charge of the synchronization with the main grid. The TSO and DSO communication with probably do not need very high bandwidth of communication [see figures below].

Data Scheme

Data	Description	Rate	Zone[from SGAM Model]6)
$\delta\omega$ [rad/s]	Secondary controller of microgrid	two data every 2-5 second	From Process to Operation
δE [V]			



(a)

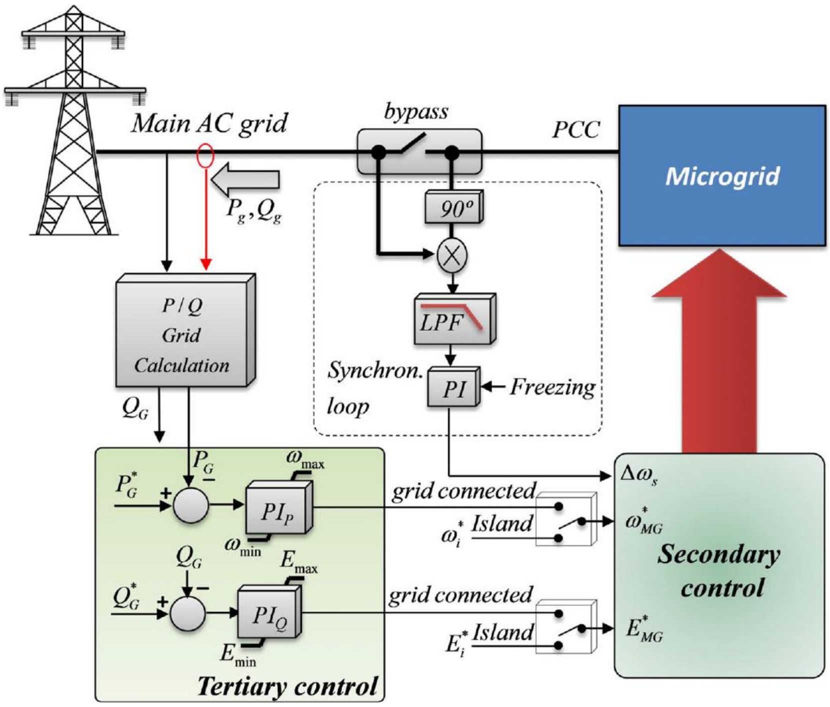


Figure 11: Hierarchical droop control typical layout taken from 10)

A.3 Smart-Net project models

Centralized AS market model (see 20)): It is most similar to the current organization of the market. The role of the DSO is limited to allowing the TSO to use resources from the distribution grid while guaranteeing that DSO grid constraints are not violated. The market for frequency control is a capacity market. This means that DSO grid constraints will be first verified during a process of system prequalification. During real-time control, the DSO will intervene at first only if severe constraints arise in the distribution grid, but the reserve activation is initiated by the TSO.

In the figure the aggregator could be (in reference with the actors under study in RESERVE) an actor which can also feed in and consume electrical energy on some level. The flexibility resource at HV level could be bulk storage system, an HVDC line connecting an offshore park, or large renewables energy power plants.

This could be a relevant structure for Sf_A where TSO will maintain a relevant role in the frequency control provision, but on the other hand there will be more need to gather and control big groups of distributed sources at the distribution level to make them relevant enough to participate to the common market. Moreover, depending on the actual organization DSO grid constraints will be poorly considered and often give rise to problems in the distribution grids.

At the beginning, DER will not cause constraints problem in the distribution grids. As they become more present, the DSO role will have to change accordingly, and procedures will become more complex, resulting in forming the second possible market organization

Common TSO – DSO AS market model. In this market structure DSO will be more involved in the process of reserve procurement. In particular, it could impose some limitation on a regular basis (hourly or even less) to the technical provision of the reserves, for instance in the change of droop settings or provision capacity. In this way, DSO grid constraints will be more integrated in the process and more reserves could be provided.

Obviously the system will be more complex: there will be a need for bigger and better communication systems, but the total costs should remain low thanks to the participation of more resources. If the DSO was involved in the procurement phase, less aggregation of DER could be considered acceptable.

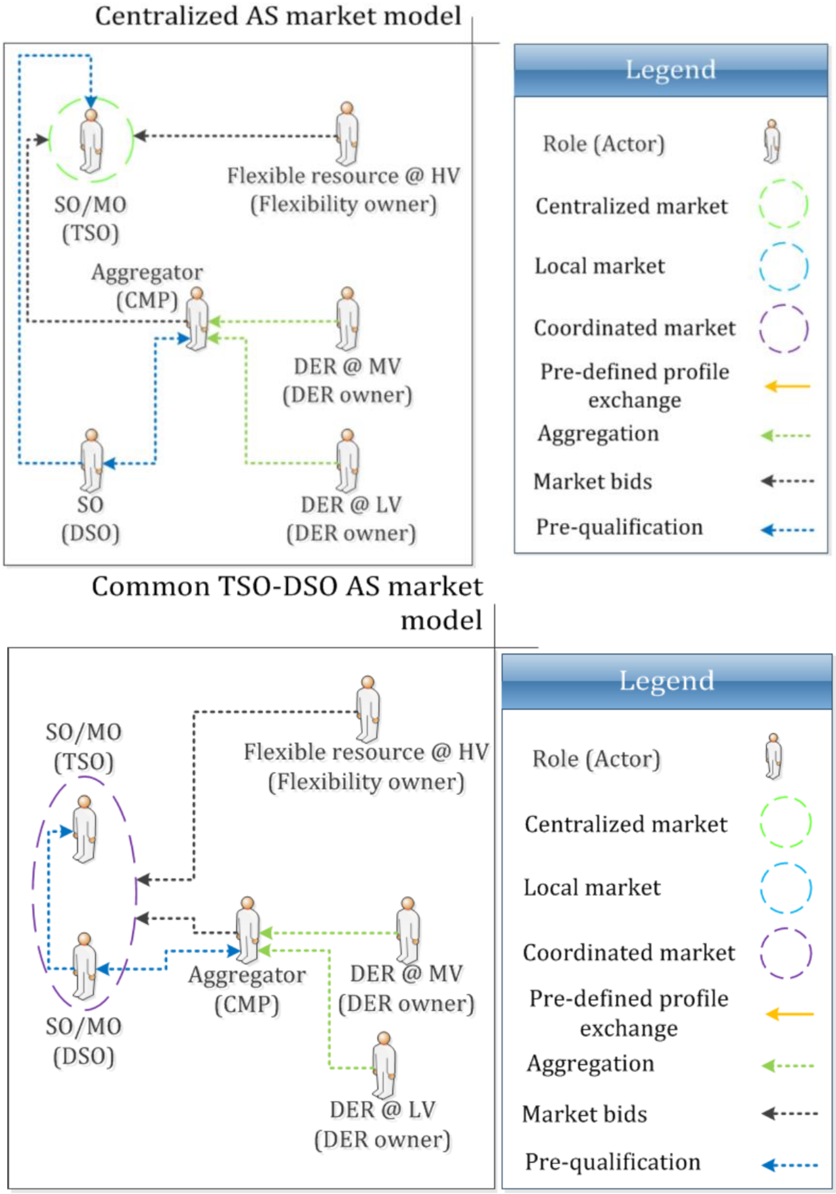


Figure 12: Centralized and Common TSO-DSO AS market organizzation (images from Smart Net Deliverable 1.3)

The market process consists of prequalification, procurement, activation and settlement procedures. These dynamics will present additional problems and complexities. The Communication requirements to sustain the market structure itself should be adequate.