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Principles of operation of grids of DC and AC subgrids interconnected by power converters

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***Abstract*—The concept of segmented AC power systems interconnected by means of HVDC is becoming more and more significant for many cases worldwide. Such systems already exist and will become more complex with the increasing emergence of HVDC links and grids. The concept of a grid composed of multiple subgrids motivates the need to define the governing roles of Interconnecting Power Converters (IPC) which connect the different subgrids. Such IPC can have various operation modes which are presented and analyzed in this paper. In addition, the principles of operation needed for each individual subgrid and for the overall system are introduced and discussed. The resulting fundamental equations are outlined and combined in a power flow formulation of the overall system. A simple case study is presented to illustrate the power flow formulation in a grid of multiple subgrids, also introducing example dynamic simulations of transitions between different operating points.**

***Index Terms*—grid of grids, AC and DC grids, AC and DC power flow, segmented systems.**

I. INTRODUCTION

Segmented AC power systems interconnected by means of HVDC are becoming more and more significant for many power systems worldwide. As an example, the current European electric power system is composed of 5 main synchronous areas which are interconnected by means of High Voltage Direct Current (HVDC) transmission systems. The different zones are operated independently, also allowing power exchange through the HVDC lines. [1]

Large system oscillations happen with certain frequency in power systems. A recent example occurred last 1st December 2016, when an unexpected opening of a line in the French system triggered an oscillatory incident in Continental Europe system [2]. These oscillations might lead to important blackouts, like the 2003 blackout in Italy produced by cascading failure, which affected 55 million consumers.

While the typical power system engineering planning approach has been for decades to build the largest possible system, recent studies suggest that such large power systems imply a risk of cascaded failures, and therefore, it would be beneficial to segment them [3], [4]. Reference [3] indicates that there is an optimal size in terms of security and risk. Small power systems are vulnerable but very large power systems can have huge blackouts. The incremental use of HVDC lines connected to an AC grid can also motivate the power system segmentation. Connecting different HVDC lines to the same AC system can lead to instability problems. Several studies in the literature reflect possible instabilities in multi-infeed HVDC systems [5]–[7]. Such systems can be vulnerable if the size of the overall AC system is too large. The segmentation of these systems by HVDC lines, known as dc-segmentation, seems to be a reliable solution [8], [9]. Such a solution is based on arranging the converters in a different way in order to decouple the original AC system into smaller AC sub-systems. In this way, HVDC converters can act as firewalls and prevent large blackouts.

A number of studies reported in the literature reinforce the idea of dc-segmentation. In [10], two AC systems are segmented by HVDC lines, concluding that the resulting power system is more robust in front of a huge blackout scenario. Based on statistical data and a proposed risk assessment method, [11] concludes that the risk of cascading outages and large blackouts are decreased with DC-segmentation. Back-to-Back VSC converters are considered in [9] to segment an existing AC system, reducing the impact of different faults to other AC areas. Moreover, [12] analyzes the optimal dc-segmentation scheme in terms of stability by the evaluation of three different stability indices. A real dc-segmentation example has already started in China, where the Yunnan zone has been disconnected from the main synchronous area, to reduce the risk of a cascaded blackout [13]. Several studies are considering the option of applying similar measures in Europe or North America [4]. These studies suggest that the grid size needs to be re-adjusted in some cases. HVDC can act as a firewall against cascading failures and as an effective separation between segmented zones.

While there is a possible (and uncertain) trend to segmented power systems, the present paper outcomes are anyhow relevant and useful if this segmentation never occurs, as some existing systems (like the actual European power system) are already segmented, and the segmentation will increase while integrating HVDC grids and remote offshore wind.

Currently, existing VSC-HVDC transmission systems in Europe use point-to-point connections [1], where each individual converter is directly connected to another converter. More terminals can be added evolving into the so-called multi-terminal HVDC (MT-HVDC) scheme. Three multi-terminal HVDC projects (Nanao [14], 3 terminals, Zhoushan [15], 5 terminals, and the most recent one, Zhangbei [16], [17], 4

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terminals with a future perspective of expansion) are already in operation in China, while some projects are under study in Europe. Furthermore, there is an opportunity to create meshed HVDC grids, interconnecting different countries and large scale renewable generation plants (mainly offshore wind, such as the so-called North Sea Supergrid [18]). An HVDC grid shows a number of advantages [1] (compared to other transmission options such as point to point HVDC or HVAC) but requires standardization and coordination. The system resulting of an eventual HVDC grid combined with offshore AC grids and different terrestrial AC grids, is a very complex system of systems which is the subject of study of the present paper.

Hybrid AC and DC systems have been studied in the literature. Several studies consider strong AC grids where DC grids are connected and focus on the control of HVDC grids, typically using droop control for the overall HVDC system stability enhancement [19]–[21]. Other studies consider the formation of AC grids with HVDC converters, using droop equations linking AC frequency and converter active power [22]–[24]. While these references propose and demonstrate appropriate control laws for converter operation, focusing either on DC or AC systems, to the best of authors knowledge there is no work defining the overall principles of operation and control for grid of multiple AC and DC subgrids.

The paper proposes a definition of operation principles to operate grids composed of multiple subgrids. The proposed operation principles are presented conceptually and also including some governing equations for the different converters and units involved in the system operation. Special emphasis is given to the so-called Interconnecting Power Converters (IPC) which interface AC and DC subgrids, while controlling relevant quantities in their respective AC and/or DC sides. The different IPC roles are investigated, considering the possibility of operating in grid forming or following mode in the AC or DC sides. A power flow formulation for the overall system comprising several subgrids is presented and exemplified in a case study.

The paper contributions can be summarized as follows:

- The principles of operation for grids composed of multiple AC and DC subgrids are presented and analyzed.
- The different existing control laws for grid-following and grid-forming converters for DC and AC sides of the converters are combined and analyzed according to the principles of operation presented.
- A power flow for grids of grids is formulated considering the combined control laws and overall system equations.
- The principles of operations presented are exemplified in a case study, including a power flow analysis and dynamical simulations.

The rest of the paper is organized as follows. Section II introduces grids of grids and discusses the trend to segment modern power systems and the emergence of HVDC grids interconnecting different AC grids. Section III, includes a classification of elements in a grid of grids, considering grid-forming and grid-following units and Interconnecting Power Converters (IPC). The operation and control principles for grids of grids are presented in Section IV. The power flow formulation combing the different units control laws is detailed in Section V. A case study to exemplify the proposed concepts is presented in Section VI and finally, the conclusions are summarized in Section VII.

II. The Grid of grids

One possible example of an actual power system is sketched in Fig. 1 (up). It can be seen that a number of different renewable energy sources and energy storage systems are connected to a large AC network with some conventional power plants and loads. Offshore wind power plants are also included in the system, one of them is connected by means of an AC cable, while the two others are connected by means of HVDC transmission.

The previously mentioned risk of overall system blackout can motivate a change of the system structure, and an eventual segmentation of the grid as shown in Fig. 1 (middle). The sketched system divides the existing AC grid into three smaller subgrids which are separated by means of HVDC transmission lines. In this way, HVDC converters can become firewalls that can prevent cascading failures in the entire power system. Power system segmentation ensures that faults are not directly seen in neighbouring networks. It is worth mentioning that segmenting and firewalling the grid does not mean that support cannot be provided from the neighbouring grids. HVDC power converters can ride through the fault and provide support to the grid which is in fault conditions. The converters connected to the faulted grid can ensure that the neighbouring grids provide the necessary support.

It is noticeable that the system being discussed is not a system difficult to imagine and far-away form the reality. In fact, the European system as it is today clearly corresponds to this kind of system, where different non-synchronous areas (continental Europe, Great Britain, Ireland, Nordic, Baltic) are interconnected by means of a number of HVDC lines. With the emergence of multi-terminal HVDC transmission systems and HVDC grids, the discussed system can eventually evolve to the configuration sketched in Fig. 1 (bottom), where different AC grids are combined with several DC grids and offshore AC grids, forming a grid of grids. The purpose of HVDC in such systems would be not only to interconnect (or to provide a firewall to) different AC systems, but to build grids based on DC technology. It can be observed that both AC/DC and DC/DC converters [25] are employed in the system.

A grid of grids can be defined as a hybrid AC-DC system which incorporates multiple AC and DC subgrids. The different AC and DC sub-systems are interconnected by means of Interconnecting Power Converters (IPC). A grid of grids has several clearly defined conceptual levels which are analyzed in the present paper, including an overall system level (grid of grids), a subgrid level (for each AC and DC subsystem) and unit level (for each converter, generator, load).

Energy markets dictate the steady-state power flows in electric power systems. Such energy markets can be considered technology neutral and do not distinguish between AC and DC systems. Only when it is technically not possible to transmit the power agreed in the markets, some restrictions need to be

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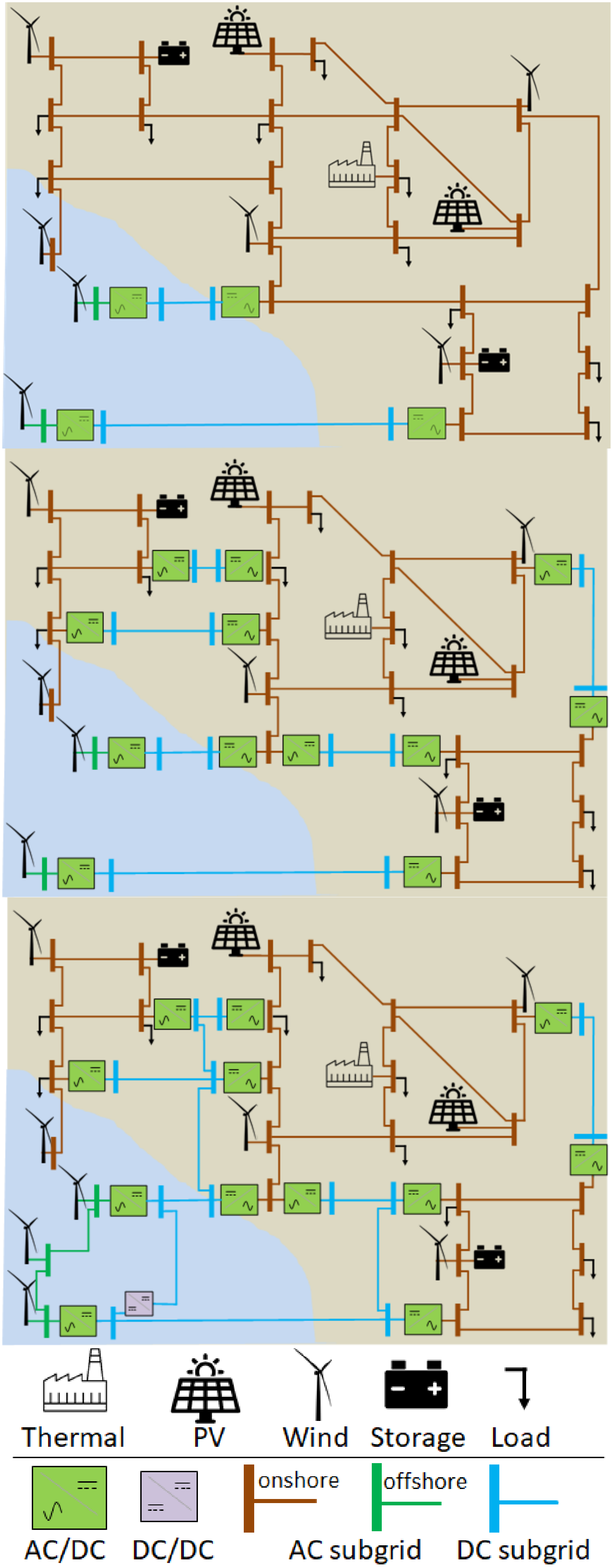

Fig. 1. Example electrical systems: non-segmented power system with some offshore wind (up), segmented power system using HVDC lines (middle), and evolution including several DC and AC grids in the system (bottom).

implemented. On the other hand, the overall system stability and the stability of each of the grids is heavily dependent on the technology deployed and the network structure.

III. Classification of Elements in a Grid of Grids

The complex grid of grids composed of multiple DC and AC subsystems includes different main elements: loads, generation sources, energy storage units, AC and DC networks and interconnecting converters. The different unit types (connected to the different DC or AC buses of the different sub-systems) can be classified according to their controllability as follows:

- Controllable. The active and reactive (AC case) power exchanged with the grid can be adjusted depending on the overall system requirements. It is important to note that the fact that a unit is controllable does not mean that it is always being controlled according to the system requirements. For example, a PV power plant will be normally injecting the maximum possible power using appropriate maximum power point tracking (MPPT) algorithms. However, if there is an excess of generation in the system, the PV power plant can rapidly adapt to it and reduce the generation accordingly. Controllable nodes can be in turn classified as
  - Grid following units. Nodes that synchronize with an existing grid and that inject a given amount of controllable active or reactive power (only active for DC). They can contribute to voltage and frequency control with additional loops where active and reactive power is adjusted to provide a given support. Examples of these units are converter based generators (PV and wind) or energy storage systems (battery based). The grid following units typically synchronize with the grid with a Phase Locked Loop (PLL).
  - Grid forming units. Nodes that form the grid and impose an angle and voltage. They can synchronize with an existing grid and also create a standalone grid. Examples of these units include conventional synchronous generation units directly connected to the grid (thermal, nuclear or hydro power plants) or power converters programmed as grid forming units. Grid forming units do not require any PLL to synchronize with the grid.

  In order to ensure the proper operation of all the individual sub-systems and the overall system, it needs to be ensured that each subsystem has at least one unit taking care of the grid formation. It is important to remark that the converter or converters taking care of the grid voltage and frequency control can be different over the time, depending on the internal state of the source and the system requirements.
- Non-controllable. They exchange a given amount of active and reactive power with the grid, regardless the overall system needs. An example of these devices are the non-controllable loads.

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A. Interconnecting Power Converters (IPC)

Interconnecting Power Converters (IPC) are the key elements that allow the interconnection of different AC and DC sub-systems. The interconnecting converters for high voltage applications can be based on different technologies: Line Commutated Converter (LCC) or Voltage Source Converters (VSC). LCC can be used as grid following units with only active power control (reactive power compensation will be required) and present serious restrictions on the dynamic performance. VSC can allow independent active and reactive power control and can be used as grid following or grid forming converters. While LCC has been used for many decades, VSC is nowadays the preferred technology for most projects. Among the different technologies proposed for VSC, Modular Multilevel Converter (MMC) technology stands as the preferred option, mainly because of the low losses that can be achieved. Two or three level based VSC use the series connection of multiple switches to operate at high voltage. MMC are cell based converters and have (limited) inherent energy storage inside the converter. This allows to transiently have different active power in the DC and the AC side of the power converter.

The option of using multiport converters interconnecting more than two systems is also possible [26] and allows the interconnection of several AC and DC subsystems. It is important to remark that the maximum number of grid forming sub-systems supplied by the converters will be equal to number of ports minus 1, as there needs to be a port supplying the power needed for the other grid forming ports. Consequently, in the case of a standard two-port converter, grid forming functionality can be provided in only one side of the converter.

B. Grid forming units

Grid forming units have the responsibility of creating the grid and controlling the voltage (and frequency for AC systems). This can be conducted imposing a voltage in a single node with a single converter unit, or alternatively it can be implemented in a coordinated manner. Different grid forming strategies have been proposed thus far, such as emulation of Virtual Synchronous Machines (VSM) [27], [28], frequency-droop approach [22], Virtual Oscillator Control (VOC) [29] and matching control [30]. As shown in [23] , different proposed methods result in equivalent overall response which basically emulate the behaviour of a synchronous generator equipped with a governor, where the rotational speed (frequency) rate of change is related to variation of active power. A mathematical formulation based on a droop control law can be adopted (as stated above it is equivalent to other definitions). The droop equation that relates the frequency and the active power can be expressed as

$$\omega_i = \omega_i^0 - k_i^p \left(p_i - p_i^*\right) \tag{1}$$

where k_i^p is the frequency droop coefficient. Similarly, the AC voltage droop can be defined as

$$v_i = v_i^0 - k_i^q \left(q_i - q_i^*\right) \tag{2}$$

where k_i^q is the voltage droop coefficient.

For DC systems, only the DC voltage can be used. The droop equation that relates the DC voltage and the DC power can be expressed as

$$v_i^{dc} = v_i^{dc,0} - k_i^{p,dc} \left(p_i - p_i^{dc,*}\right) \tag{3}$$

where $k_i^{p,dc}$ is the voltage droop coefficient.

C. Grid following units

The role of the converter in such a case consists of the control of the active power flowing through the converter, and the reactive power exchanged in the AC side. Both set-points can be constant reference values, although it is possible to implement grid support schemes with a droop characteristic. It is important to remark that the grid support is conceptually different from the grid forming approach discussed in the previous Subsection. Grid support adjusts the power to provide the required response to the grid, but it does not form the grid. Therefore, grid following units providing grid support need to synchronize with the existing grid.

In terms of active power, frequency support can be implemented as

$$p_i = p_i^0 - k_i^p \left(\omega_i - \omega_i^*\right) \tag{4}$$

where k_i^p is the active power-frequency droop constant. On the other hand, reactive power is related to voltage support (i.e., reactive power will increase whenever there is a drop in voltage amplitude, and vice versa). The corresponding droop equation in that case is

$$q_i = q_i^0 - k_i^{colorblueq} \left(v_i - v_i^*\right) \tag{5}$$

where k_i^q is the reactive power-voltage amplitude droop constant.

For DC systems, the DC power can be adjusted depending on the DC voltage as

$$p_i^{dc} = p_i^{dc,0} - k_i^{v,dc} \left(v_i^{dc} - v_i^{dc,*}\right) \tag{6}$$

IV. Operation and Control Principles for a Grid of Grids

The Section presents the operation and control principles to combine the different units analyzed in Section III in order to ensure that the overall system and all the subsystems are properly operated and controlled.

The example system of Fig. 1 discussed in Section II can be redrawn into the scheme of Fig. 2, where the different grids are clearly identified. The system includes 4 AC sub-systems (one of them offshore) and 3 DC sub-systems. The overall system control of a grid of grids like this one needs to ensure the following:

- The scheduled power flows need to be ensured in normal conditions.
- In fault or constrained network conditions, the power flows need to be as close as possible to the set-points. In these conditions, the support from neighbouring grids needs to be provided by appropriately using the power converters.

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- The power balance in the overall system and in each subsystem (grid) needs to be maintained.
- Power converters may need to be responsible for contributing to the grid formation. As IPCs can provide grid forming functionality only in one side, it will be needed to identify the optimal role (grid forming or following in the DC or AC side) for each IPC. These roles can eventually change depending on the overall system configuration and state.
- The frequency control in all the AC grids needs to be ensured. However, not always the frequency will have meaning of power balance, as there might be grids without any synchronous machine. In such a case, the meaning of frequency can be programmed as needed.
- Voltage control needs to be implemented, both for AC and DC grids.
- Stability needs to be enhanced both at the overall system level and for each individual grid.
- Ancillary services need to be provided between the different grids.

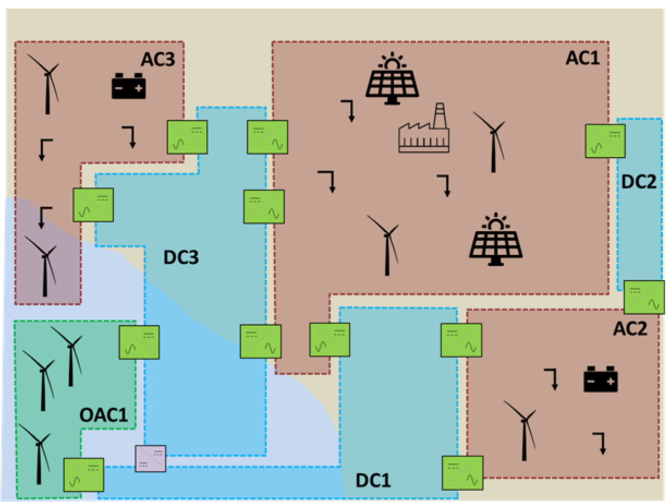

Fig. 2. Re-sketch of the example of Fig. 1, showing the different grids formed.

A. Overall operation and control approach

The overall operation and control approach can be based on the assumption that the grid of grids system can be operated analogously to normal power systems, taking into account specific restrictions.

A centralized energy and power management system will be responsible for setting all the active and reactive power set-points in all the different controllable devices. In each device, the given set-point will be combined with the required primary and secondary controllers which will be implemented locally.

The operation principles can be defined as follows:

- Principle 1. There must be at least one node (in the overall system) with grid forming capability which is not an interconnecting converter. This node can be an energy storage device or a generation unit. It is desirable (for system security and resilience) to have several non-IPC nodes with this capability. These nodes will be fundamental for the system start-up (energization), since they will be the first ones forming the grid during the start-up process. It can be noted that IPCs cannot do this role, because in the case of an overall system blackout, they will not be able to energize any subsystem.
- Principle 2. Each system subgrid will require at least one grid-forming unit (which can be an IPC or another type of unit). If more than one grid-forming unit is active, they need to be coordinated as discussed above (either using droop controllers, synchronous machine emulation, etc.). As the nature of one unit can change over the time, the overall system controller will define it at every specific instant. It is important to note that IPC can be grid-forming only in one side, as they cannot form the AC and DC grid at the same time (unless they had energy storage). Therefore, it will be important to properly assign the grid-forming roles.

  Figure 3 shows an example of the overall system start-up and energization after a blackout. The first step is the energization of subgrids AC2 and AC3 which have some sources able to energize the subgrid (these units will be grid-forming according to Principle 1). Once these subgrids are energized, IPCs can be used to energize the neighboring subgrids. Finally, the remaining subgrids are energized by additional IPCs. As discussed in Principle 2, at least one of the IPCs energizing a subgrid needs to have grid-forming capability.

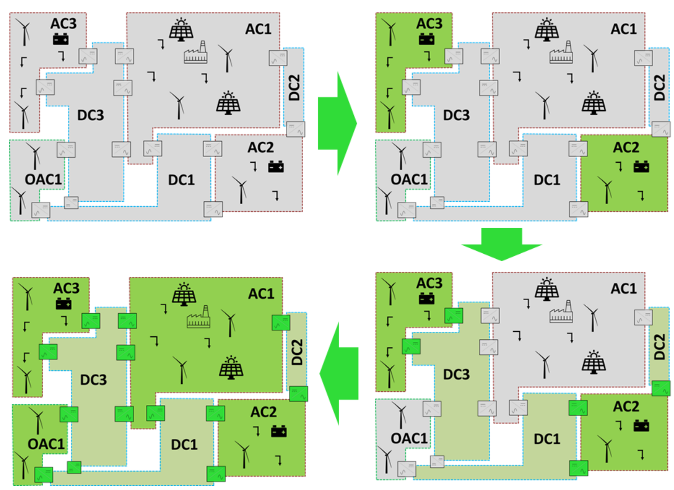

Fig. 3. Example of the overall system start-up and energization.

- Principle 3. The voltage and frequency (for AC cases) of all the different subsystems needs to be maintained as close as possible to the scheduled set-points. In normal conditions, when the load and generation changes the overall system has to adapt fast to new power flows. When there is a severe perturbation in one sub-system, the neighboring systems can provide support through the IPC. The support they can provide will be limited and dependant on the availability of the different sources and potential flexibility of the different units.
- Principle 4. The overall system stability and the stability of each subsystem needs to be ensured by a number of

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different units which need to be coordinated. Therefore, the controllers of the different units in the system may need to include specific control functionalities to damp dangerous oscillations or to prevent resonances. IPCs can allow to enhance the stability in one grid, but some actions can risk the stability of the other system which is interconnected to it. It is important to take into account the additional flexibility of MMC converters as they can use their inherent energy storage to minimize the impact in neighboring grids while providing support.

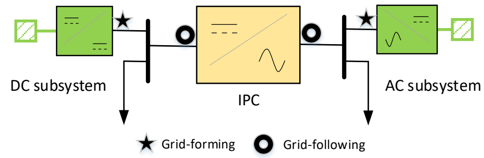
- Principle 5. The overall controller will provide reliable operating points which allow the system to perform properly during sudden changes or eventual perturbations. This needs to be taken into account in the active and reactive power dispatch. The set-points will be sent through a communication system. The signals will be sent periodically and the communication will allow optimal overall system operation, but the electrical stability will be governed by the local units. Set-point calculation needs to ensure that the local unit has enough regulation margin to cope with different electrical contingencies. The severe limitations established by the power electronic converters need to be considered. Power electronics converters cannot be significantly overloaded and therefore converters will have to saturate in some operating conditions. This can jeopardize the overall power system stability. This principle requires to take into account the above comments and ensure that the operation points scheduled guarantee that the system will remain stable if any contingency occurs.

B. Simplest grid of grids case

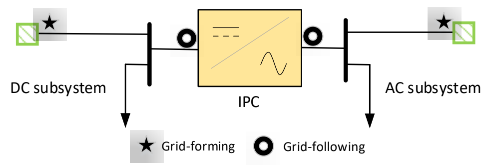
In order to easily understand the different operating modes of the different elements of the system, a scenario consisting of two subsystems (DC and AC) interconnected by a converter is presented, which can be seen as the simplest possible case of a grid of grids. The possible roles of each element of the system can be described in the following three scenarios. It can be noted, that the principles 1 and 2 are defined in a different way in the different scenarios. Regarding principles 3, 4 and 5, all the scenarios will ensure voltage and frequency support among subsystems (Principle 3), stability enhancement (Principle 4) and reliable operation points scheduling (Principle 5)

1) Scenario 1 - Full grid-following: One possibility is to assign the grid forming functionality to the two sources connected to each subsystem, and let the interconnecting power converter (IPC) control the power flow between the two sub-systems, according to a given power set-point. The external grid forming units can be implemented either by power converters (Fig. 4a) or by external grids (Fig. 4b). Although only the case with converters is shown in Fig. 5 and 6, this also applies for those scenarios. Note that in the AC side case, a single synchronous machine would be enough to form the grid.

This case can be analyzed as follows. The source connected to the DC subsystem will regulate a constant voltage v_{dc} (coordination schemes are not needed as it is the only source



(a) Grid-forming converter in the AC side



(b) Grid or synchronous generator in the AC side

Fig. 4. Sketch of a simplified system where the two sources are the grid forming units.

with grid-forming capability). Similarly, the source connected to the AC subsystem will regulate the voltage and frequency to v_{ac} and ω_{ac}, respectively. If the loads consume a power $p_{dc-load}$, $p_{ac-load}$ and $q_{ac-load}$, and the IPC exchanges a power of p_{ipc} (assuming positive value when the power flows from the DC to the AC side), the DC source will need to inject a power of $p_{dc-1} = p_{dc-load} + p_{ipc} + \alpha p_{losses}$ and the AC source $p_{ac-1} = p_{ac-load} - p_{ipc} + (1-\alpha)\, p_{losses}$ and $q_{ac-1} = q_{ac-load} - q_{ipc} + q_{grid_{a}c}$, where the active power losses of the IPC and the grid elements are assumed to be shared between the two sources with a ratio α, and the AC grid and load reactive power is supplied by the AC source and the IPC.

Principles 1 and 2 are secured by using two external sources as grid forming nodes. In this case, the IPC has no grid-forming functionality. The system start-up can be impemented in the two sides separately.

2) Scenario 2 - Single grid-forming: The grid-forming functionality can be assigned to the interconnecting power converter, letting one of the sources be controlled as a power injecting unit. In this case, only one of the two sub-systems which the interconnecting power converter is interlinking will have a grid formed by the IPC, while the other one will exchange the power required (see Fig. 5). In Fig. 5a, the IPC operates as a grid-forming AC node, exchanging the AC power required by the AC elements, which in turn will be supplied or absorbed by the DC units. In Fig. 5b the IPC operates as a grid-forming DC node, exchanging the DC power required by the DC elements, which in turn will be supplied or absorbed by the AC units.

Principles 1 and 2 are secured by using one external source as grid forming node and using the IPC to form the grid in the other side. The start-up of the system will require first the energization of the side with the grid forming source, and afterwards the IPC will be able to energize the other side.

3) Scenario 3 - Multiple grid-forming: Grid-forming capability can be considered in more than one unit. This option is sketched in Fig. 6, where the IPC and one source are operated

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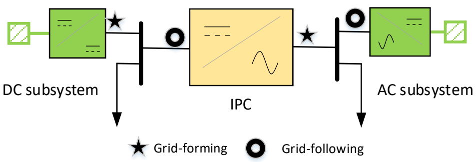
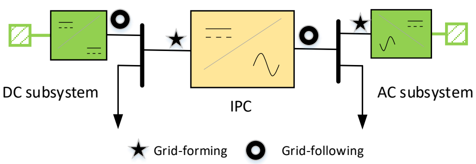


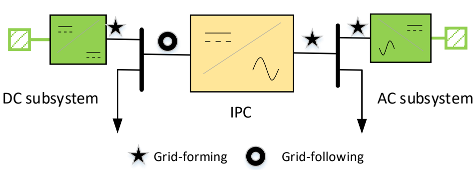
(a) Source DC and IPC AC side as grid-forming



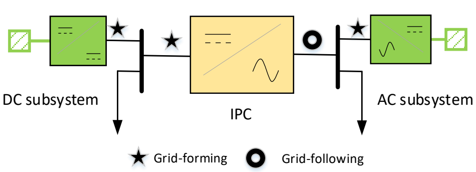
(b) Source AC and IPC DC side as grid-forming

Fig. 5. Sketch of a simplified system with one source and the IPC as grid-forming units.

to provide the grid forming capability in a coordinated manner. In the upper subfigure, there are two converters which have to be coordinated in the DC side to ensure the DC subsystem operation. In this case, the DC power required by the other DC elements will be shared by both converters. In the lower subfigure, an equivalent configuration is obtained in the AC side. In that case, the AC power required by the other AC elements will be shared by both converters. Assuming that reactive power is something to deal with separately (this will be true as long as the power converter limits are not reached), the case in the AC and DC sides can be analyzed similarly.



(a) Source dc, AC and IPC AC side as grid-forming



(b) Source dc, AC and IPC DC side as grid-forming

Fig. 6. Sketch of a simplified system with both sources and the IPC as grid-forming units.

When more than one unit is forming the grid (e.g., synchronous generators or converters) the frequency of the system stabilizes at a particular value. Assuming all grid-forming units can be modelled through a power-frequency droop characteristic, one can be taken as the reference, and the i grid-forming unit satisfies $\omega_i^0 - k_i^p\left(p_i - p_i^*\right) = \omega_0^0 - k_0^p\left(p_0 - p_0^*\right)$

Principles 1 and 2 are secured by using two external sources as grid forming nodes and additionally using the IPC to form the grid on of the sides. This requires coordination between grid-forming nodes, but allows to start-up the system in both sides independently.

V. Power flow formulation

A power flow formulation for a grid of grids is introduced to allow a steady-state analysis of the system, considering different possible operation modes. Power flow formulation for a grid of multiple subgrids requires to take into account both the traditional power flow equations for each AC and DC subsytem and the governing equations of interconnecting converters,

A generic grid can be defined with N_{ac} AC subgrids and N_{dc} DC subgrids, where each AC subgrid i has N_{n-ac}^i nodes and each DC subgrid j has N_{n-dc}^j nodes. The number of interconnecting converters (to ensure power exchange overall the system) has to satisfy $N_{IPC} > N_{dc} + N_{ac} - 1$.

Each AC node includes 4 key quantities: voltage, angle, active and reactive power. Overall, each AC i subgrid includes an overall grid frequency f_{ac}^i or equivalent angular frequency $\omega_{ac}^i = 2\pi f_{ac}^i$. Therefore, to define each AC node, it is needed that the number of known quantities plus defining equations is exactly 4. In addition, defining equations for the overall AC frequency will be needed (the simplest case would be the equation $f_{ac}^i = 50$ Hz). If nodes including frequency droop are included, the following equations need to be satisfied:

$$\underbrace{\omega_i^0 - k_i^p\left(p_i - p_i^*\right)}_{\omega_i} = \dots = \underbrace{\omega_N^0 - k_N^p\left(p_N - p_N^*\right)}_{\omega_N}, \tag{7}$$

where the number of equations will be equal to the total unknown angular frequencies ω_{ac}^i minus 1.

Each DC node includes 2 key quantities: voltage and power. To define each DC node, it is needed that the number of known quantities plus defining equations is exactly 2. IPC nodes (as they include one AC plus one DC side) will need the number of known quantities plus defining equations to be exactly 6. IPCs will have to consider that in steady state, the only difference between AC and DC power is due to the converter losses.

Considering all the possible operating modes of AC and DC nodes in such a grid, it is necessary to extend the classical classification of nodes which is normally used in a power flow formulation. It has to be noted that depending on the operating mode of each IPC, different equations related to the AC and DC sides have to be used.

An important feature which needs to be analyzed is the existence of a node that is imposing the AC subsystem frequency. If it exists, this node will be both imposing the subsystem reference angle and the subsystem frequency ω_i for all the nodes belonging to the subgrid. If such a node does not exist (and this will be the case of distributed slack schemes) then it is needed to define the reference angle at any node in the subsystem and let the frequency be found as a result of the power flow analysis.

The generic power flow equations for AC nodes can be written as

$$p_i = \sum_{k=1}^{N} v_i v_k \left(g_{ik}\cos\theta_{ik} + b_{ik}\sin\theta_{ik}\right) \quad (8)$$

$$q_i = \sum_{k=1}^{N} v_i v_k \left(g_{ik}\sin\theta_{ik} - b_{ik}\cos\theta_{ik}\right), \quad (9)$$

where p_i and q_i are the net active and reactive powers externally injected in node i.

The different types of AC nodes can be classified as follows (see Table I):

- Slack node: voltage amplitude, frequency and angle are known. The frequency and the voltage amplitude can be either fixed or obtained through its respective droop laws, using P and Q, respectively.
- Distributed slack: in case more than one slack is present in the same AC subsystem, the distributed slack approach can be adopted. In this case, one of the distributed slacks should be taken as the reference with a fixed $\theta_i = 0$, and the others should be left with an unknown angle and the condition of frequency equilibrium. In this node, the frequency will be linked to the active and the voltage will be known (or it will define a droop law linking voltage and reactive power).
- PV node: the exchanged active power P and voltage amplitude V are known. This is common in generating nodes operating at a given scheduled operating point.
- PQ node: the exchanged active and reactive powers P and Q are fixed. Intermediate nodes of the grid that are not explicitly Slack or PV, can be considered as PQ with P$=0$ and Q$=0$.
- BPV node: Balancing PV nodes refer to the IPC nodes operating as PV where P is defined in the DC side.
- BPQ node: Balancing PQ nodes refer to the IPC nodes operating as PQ where P is defined in the DC side.

For BPV and BPQ nodes the balancing equation will be defined as:

$$P^{ac} = P^{dc} - P_{losses} \quad (10)$$

TABLE I
TYPES OF AC NODES

Type	Known	Unknown	Equations
Slack	$v_i\ \theta_i$	$p_i\ q_i$	(8) (9)
Distributed slack	v_i	$p_i\ q_i\ \theta_i$	(7) (8) (9)
PV	$p_i\ v_i$	$q_i\ \theta_i$	(8) (9)
PQ	$p_i\ q_i$	$v_i\ \theta_i$	(8) (9)
BPV	v_i	$q_i\ \theta_i$	(8) (9) (10)
BPQ	q_i	$v_i\ \theta_i$	(8) (9) (10)

Regarding DC nodes, the power flow equation can be written as

$$p_i^{dc} = \sum_{k=1}^{N} v_i^{dc}\left(v_k^{dc} - v_i^{dc}\right) g_{ik} \quad (11)$$

The different types of DC nodes can be classified as follows (see Table II):

- Slack node: The DC voltage is defined. This role typically corresponds to a master converter in a point-to-point link or in a multi-terminal grid. In the latter, only one converter can operate as a master. Otherwise, the multi-terminal grid will contain multiple distributed slacks.
- Distributed slack: The DC voltage is known, usually given by a droop characteristic to locally achieve power sharing. This can be found in multi-terminal grids with multiple converters controlling the DC voltage.
- P node: The power is defined. This could be the case of a DC load, generation or interconnecting converters (where the power is defined in the AC side).
- BP node: Balancing P nodes refer to the IPC nodes where the active power is defined in the AC side.

For BP nodes the balancing equation will be defined as:

$$P^{dc} = P^{ac} - P_{losses} \quad (12)$$

TABLE II
TYPES OF DC NODES

Type	Known	Unknown	Equations
Slack	v_i^{dc}	p_i^{dc}	(11)
Distributed slack	-	$v_i^{dc}\ p_i^{dc}$	(3) (11)
P	p_i^{dc}	v_i^{dc}	(11)
BP		$v_i^{dc}\ p_i^{dc}$	(11) (12)

The role of interconnectors is fundamental for the correct operation of the multigrid system. As it has been stated above, the interconnectors will have different roles in the two sides where they are connected. This needs to be considered in the power flow formulation.

VI. CASE STUDY

In this section, a case study of a grid of grids is presented. The system is formed by three AC subsystems and two DC subsystems. The system under study is depicted in Fig. 7.

As pointed out in Section IV there must be at least one unit with grid forming capability in the overall system (Principle 1). There are 2 grid forming units which are not an IPC, one in the AC 1 (SG in Node 1) and another one in the AC 2 (SG in Node 8). Moreover, Principle 2 is also accomplished as each subgrid has grid-forming units. Apart from the referred SG in AC subgrids 1 and 2, the AC subgrid 3 includes an IPC in grid-forming mode. In the DC subgrids, multiple IPCs are coordinated to form the DC voltage. In the DC subgrid 1 these are IPC A and B, while in the DC subgrid 2 these are IPC D and F.

The node definition is shown in Table III. The definition is fundamental to conduct the power flow analysis of the overall system. The total number of unknowns, equations and definitions is illustrated in Table III. The different subsystems include distributed slack nodes (DSK), slack nodes (SK), PQ, PV, BPQ, BPV and BP nodes for the different AC and DC subgrids. Table III includes the type of node, the unknowns associated to the node, the variables defined directly or by means of the IPC imposition (DC and AC side power need to be equal), the power flow equations defined in (8), (9) and (11) and the droop equations.

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The power flow results are shown in Fig. 8. Note that the base values are V_{b1} =280 kV, V_{b2} =220 kV, V_{b3} =320 kV, V_{dc} =640 kV, S_b =1000 MVA, W_b =40 MJ.

A dynamic simulation is shown in Fig. 9 conducting several changes and events in the overall system. In the initial state, three loads are already connected to the system. Two of them are placed in AC subgrid 1. These are located in Node 2 (150 MW, 50 MVar) and Node 3 (75 MW, 50 MVar). The third one, in the AC subgrid 2, is placed in Node 9 and it is absorbing 250 MW. The loads remaining are all disconnected from the respective AC subgrids and the wind-farms and PV panels are not injecting power to the different grids. At t =0.3 s, Node 5 increases the load from 0 to 100 MW and from 0 to 50 MVar; the wind-farm in Node 3 starts injecting 150 MW at t = 0.5 s. In the AC subgrid 2, at t =0.7 s; Node 7 increases the load from 0 to 250 MW and from 0 to 50 MVar. In the same subgrid the PV plant at Node 6 increases the generation from 0 to 100 MW at t = 0.9 s. Finally, the power-flow steady-state operation is reached when the IPC C changes its active power reference from 0 to 250 MW. In all these different events, the overall system demonstrates a fast adaptability to the new power-flow solution complying with Principle 3 and 5.

A three-phase to ground fault is simulated in Node 3 at t =1.5 s and recovered at t =1.7 s. As shown in Figure 9 the IPC provides appropriate support to the faulted network and secures system stability as described in Principle 4. This support is provided without risking the stability of the neighboring subgrids.

Finally, IPC F is disconnected from the AC subgrid 2 at t =2 s. The overall system adapts correctly to a new stable point. Sub-system AC 1 supports AC 3 absorbing the power excess from the wind farm in Node 11.

TABLE III
AC AND DC NODES DEFINITION OF THE CASE STUDY

Sub grid	N	Type	Unknown	Variable defined	IPC defined	PF eqs	Droop eqs
AC1	1	SK	$P_1^{ac}Q_1^{ac}$	$V_1^{ac}\theta_1$		PQ	
	2	BPV	$P_2^{ac}Q_2^{ac}\theta_2$	V_2^{ac}	P_2^{ac}=P_1^{dc}	PQ	
	3	PQ	$V_3^{ac}\theta_3$	$P_3^{ac}Q_3^{ac}$		PQ	
	4	BPV	$P_4^{ac}Q_4^{ac}\theta_4$	V_4^{ac}	P_4^{ac}=P_2^{dc}	PQ	
	5	BPV	$P_5^{ac}Q_5^{ac}\theta_5$	V_5^{ac}	P_5^{ac}=P_4^{dc}	PQ	
AC2	6	PQ	$V_6^{ac}\theta_6$	$P_6^{ac}Q_6^{ac}$		PQ	
	7	PQ	$V_7^{ac}\theta_7$	$P_7^{ac}Q_7^{ac}$		PQ	
	8	SK	$P_8^{ac}Q_8^{ac}$	$V_8^{ac}\theta_8$		PQ	
	9	BPV	$Q_9^{ac}\theta_9$	$P_9^{ac}V_9^{ac}$		PQ	
AC3	10	SK	$P_{10}^{ac}Q_{10}^{ac}$	$V_{10}^{ac}\theta_{10}$		PQ	
	11	PQ	$V_{11}^{ac}\theta_{11}$	$P_{11}^{ac}Q_{11}^{ac}$		PQ	
DC1	1	DSK	$V_1^{dc}P_1^{dc}$			P	(3)
	2	DSK	$V_2^{dc}P_2^{dc}$			P	(3)
	3	BP	$V_3^{dc}P_3^{dc}$		P_3^{dc}=P_6^{ac}	P	
DC2	4	DSK	$V_4^{dc}P_4^{dc}$			P	(3)
	5	BP	$V_5^{dc}P_5^{dc}$		P_5^{dc}=P_{10}^{ac}	P	
	6	DSK	$V_6^{dc}P_6^{dc}$			P	(3)

VII. CONCLUSIONS

The paper addressed grids of multiple AC and DC subsystems. There exist multiple non-synchronous AC power systems in the world interconnected by means of HVDC links. Such systems can be considered segmented AC sub-systems which can exchange power using HVDC converters. Furthermore, it can be envisaged that HVDC grids will emerge interconnecting different AC subgrids, and therefore the resulting system will be a grid of multiple AC and DC subgrids. The different subgrids would be interconnected by Interconnecting Power Converters (IPC). The different segmented power subsystems need to remain stable and provide support to the other subgrids in normal and fault conditions. The present paper explored the main principles which are needed to operate the individual subgrids and the overall system. The key governing equations which can be adopted were introduced, discussed and applied

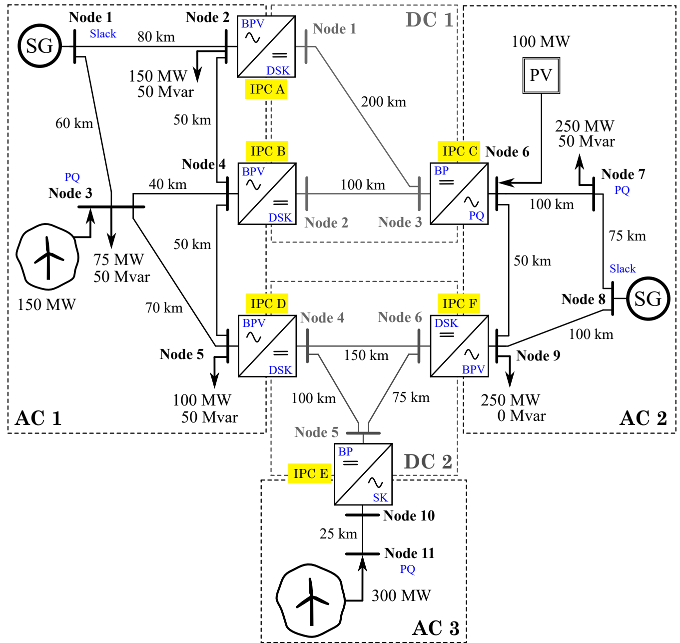

Fig. 7. Case study of a grid of grids

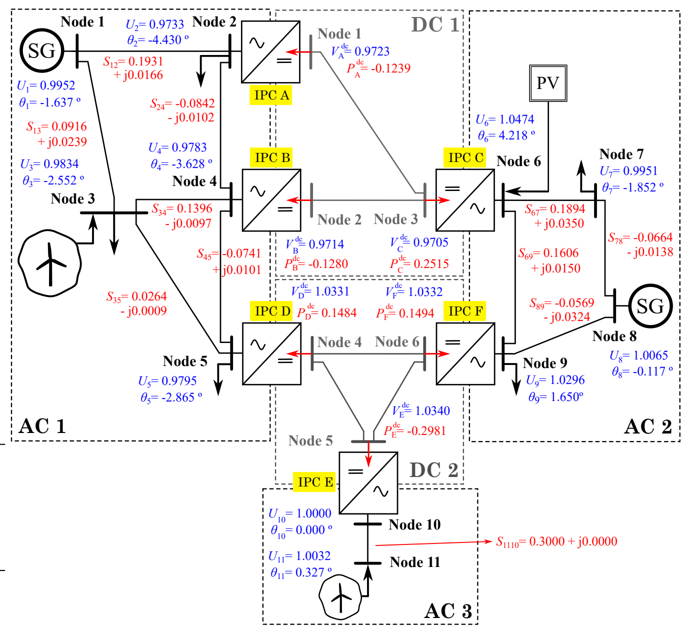

Fig. 8. bluePower flow solution of the case study (voltages and powers in p.u.)

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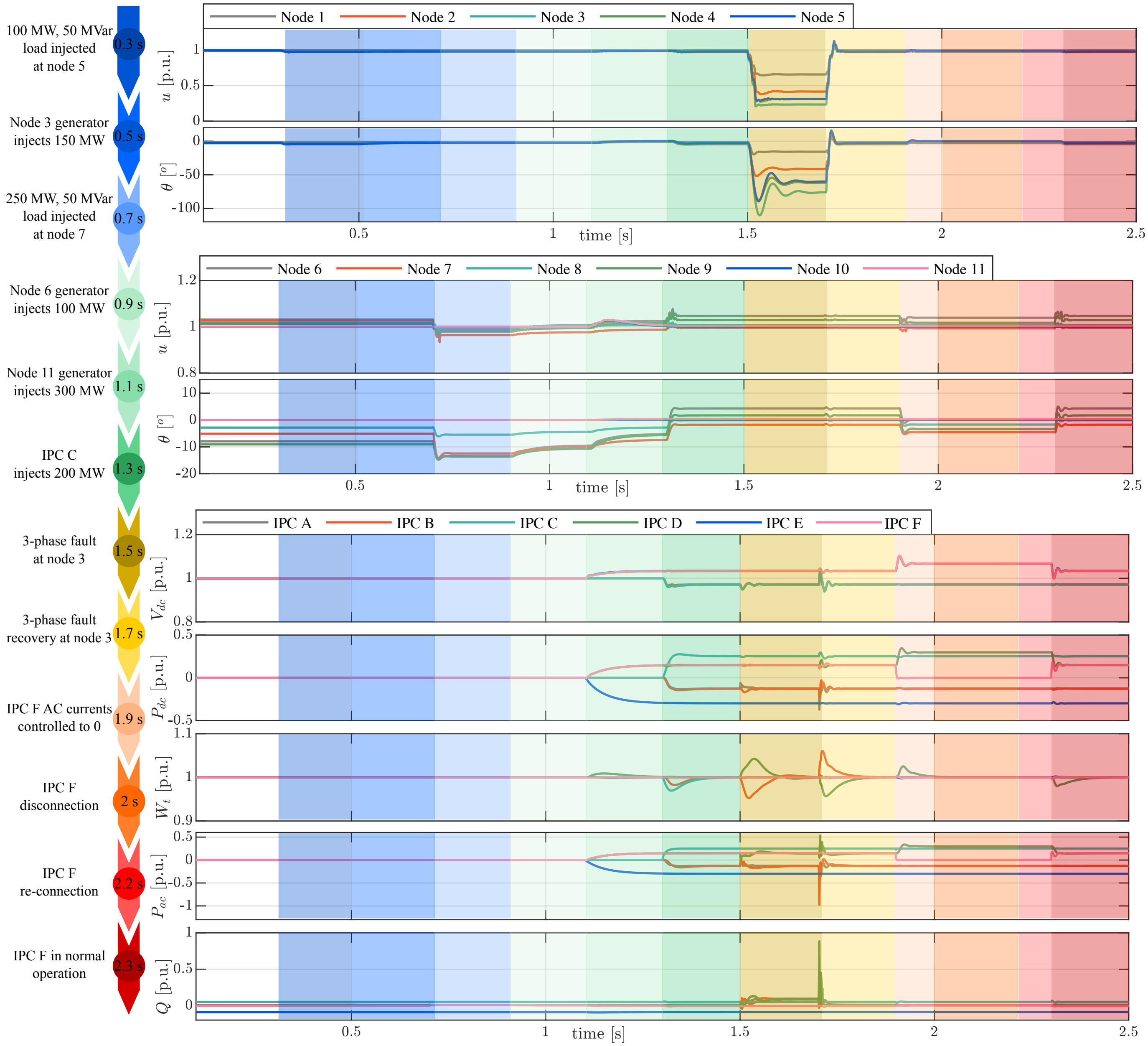

Fig. 9. Dynamic response of relevant magnitudes of the system during different changes.

to the formulation of a power flow problem. The proposed concepts where exemplified in a case study, including the power flow analysis and simplified dynamic simulation results. The paper presented the fundamental principles of operation. Further work is needed to analyze in depth the modeling of the grid of grids and the analysis of the system stability.

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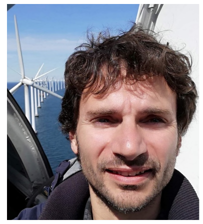

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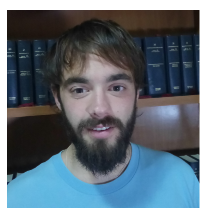

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