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DC MICROGRIDS FOR GRID INSTABILITY MITIGATION AND VIRTUAL INERTIA ANCILLARY SERVICE IN 2030 SCENARIOS

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ABSTRACT

International energetic agreements define future targets to push the decarbonization process by renewables increasing. Their deep penetration in AC grids will determine limited and alternating operative modes of traditional Synchronous Generators. In such scenarios, instabilities will not intrinsically be balanced causing inertia critical conditions. In this paper a dual approach is proposed to mitigate the problem. The strategy constituted by preventive and solving actions employ DC microgrids to locally include and manage suitable Variable Energy Resources amount and to assure prompt virtual inertia provision to the AC grid. 2030 case studies for an Italian city are analyzed.

Keywords: DC microgrids, energetic transition, frequency instability, inertia, RES, RoCoF, virtual inertia

1. INTRODUCTION

The energy transition represents a complex and not straightforward process aiming to mitigate climate change. Its goal consists in reducing CO_2 emissions through decarbonization pathway and deep Renewable Energy Sources (RES) involvement and grid integration. In this context, electrification and global electric systems must play a great role. In last years different international and national protocols were developed to push toward decarbonization [1].

In Italy, the “Piano Nazionale Integrato Energia e Clima” (PNIEC) was implemented to define the environmental and energetic approach toward zero-carbon scenarios [2]. Italy intends to pursue a coverage target of 30% of the gross final consumption of energy from renewable sources, outlining a path of sustainable growth of 33 Mtoe. In detail, photovoltaic (PV) and wind generation, starting from 31 GW, has to reach about 75 GW in ten years (2030). This scenario, entirely positive at first impression, hides high risks and problems: the deep penetration of Variable Energy Resources (VERs), with their intermittent nature, requires attention and solutions to guarantee reliable energetic supply. In fact, consequent criticalities concern power fluxes inversions, “duck curves” with load ramp absorptions at RES shutdown. Low short circuit power, grid voltage and frequency stability represent some tasks to face.

This paper aims to focus the attention on low inertia and consequent frequency instabilities affecting traditional AC grid in case of high VERs penetration.

Traditional power plants are characterized by synchronous generators converting a prime mover mechanical power in AC electrical power. They are able to limit generation/consumption unbalance by their inertial response [3]. VERs connection to AC grids is carried out by Inertia Free Generators (IFG). It determines synchronous generators switch off with consequent grid critical operating conditions.

Different approaches to low-inertia problems have been proposed in literature. In detail, Synchronous Generators inertia can be emulated by means of conventional systems such as synchronous condensers and turbines [4]. Virtual inertia can be obtained also by emerging solutions [4] such as DC-link capacitors, pumped hydro, SuperCap and ultraCaps, flywheels and batteries. Other approaches involve Virtual Synchronous Generators (VSG) and Virtual Synchronous Converters (VSC) connected to AC [4-5] and DC systems. In [5] a classification about virtual inertia techniques and their logic implementations is carried out reporting Inertia Emulation (IE), SynchronVerter (SV), Current-Controlled Virtual Synchronous Machine (CCVSM) and Voltage-Controlled Virtual Synchronous Machine VSM (VCVSM) systems. [6] proposes Electric Vehicles (EVs) intervention to primary frequency control analyzing techno-economic trade-off and underlining achievable advantages. In [7-9] frequency instability problems are faced employing wind turbines. In detail, they focus on multi-objectives approaches to the optimization of inertia constant and wind generators controller parameters. [9] considers inertia criticalities reporting mitigation applications and guidelines obtainable by wind generators. Wind farms and Energy Storage Systems (ESS) participate to integrated strategies to assure frequency control. A hybrid (SMES + battery) storage system is proposed in [10] to face low inertia criticalities in isolated microgrid.

Furthermore, in literature, few studies [5,11-12] are reported about DC microgrids virtual inertia strategies to improve the DC bus stability. In some manuscripts, DC microgrids (MGs) intervention is also proposed to mitigate the Rate of Change of Voltage (RoCoV) as reported in [5].

The attention is here focused on DC MGs as promising solutions to future grids inertia lack. This paper proposes a dual approach consisting in preventing and solving actions to assure frequency instabilities mitigation and virtual inertia provision.

The paper is organized as below reported. Frequency instability problems in low-inertia grids are debated In Section 2. DC MGs main features are reported in Section 3 focusing the attention on the considered architecture.

Section 4 is dedicated to the proposed dual approach involving DC MGs to prevent instability events and to provide Virtual Inertia Service to the main AC grid.

2. POWER SYSTEMS INERTIA

2.1 Inertia and frequency

Electric power systems were characterized by generation, transmission and distribution building blocks to which residential and industrial loads were added. In that condition, Synchronous generators intrinsically solve instabilities by their inertia (Fig.1).

According to their functioning laws, the total inertial mass M and the Rate of Change of Frequency (RoCoF) formulas are reported in Eq.1 and Eq.2 respectively.

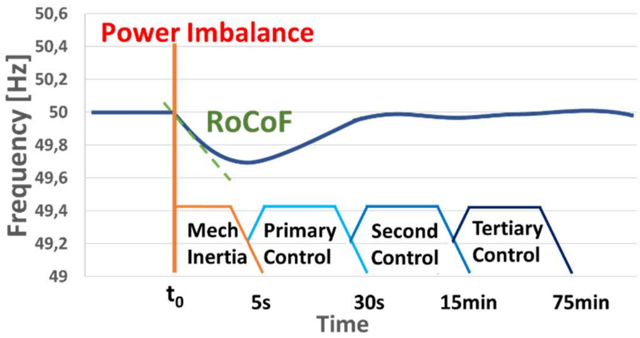

Fig 1 Frequency variation and hierarchical regulation in traditional power systems

$$M = \sum M_i = 2 * H_{eq} * \frac{A_{n\_eq}}{f_0} \quad (1)$$

$$RoCoF = \frac{df}{dt} = \frac{\Delta P}{M} \quad (2)$$

where M_i represents the inertial masses of grid synchronous generators, H_{eq} is the generators equivalent inertia constant A_{n_eq} is the generators apparent power, f_0 is the grid frequency, ΔP represents the generation loss causing the frequency variation.

Then the wide diffusion of RES has changed the traditional energetic paradigm including a myriad of small and medium generators able to inject energy into the main grid. This process has carried out to thousands of installed plants containing thousands of operative Inertia Free Converters. Their low/absent inertia (Fig. 2) causes grid critical operating conditions.

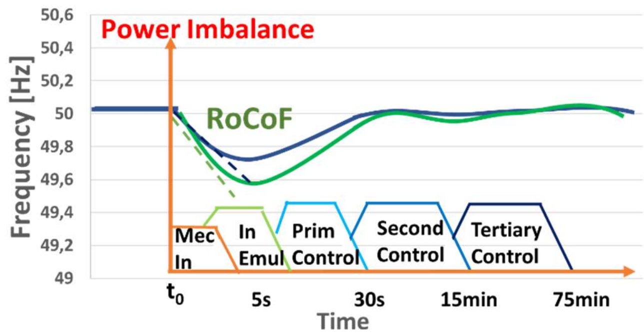

Fig 2 Frequency variation in classical (blue) and recent power systems(green) and regulation in low-inertia grids

The above-mentioned conditions will worsen during the next ten years. In fact, decarbonization protocols fulfillment will determine great VERs generation and further inertia decrease due to synchronous generators shut down. High energy production and its simultaneous grid injection will deteriorate power systems performances and reliability.

Certainly, novel solutions must be designed and developed to face problems due to IFG.

3. DC MICROGRIDS

Recently research and industrial parties have focused the attention on DC MGs underlining strength point and drawbacks [13-21]. But what are DC MGs? Could they contribute to the virtual inertial response so mitigating grid frequency instabilities?

The US Department of Energy defines a MG as "a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected and island mode [22]." The above mentioned definition is based on three requirements: 1) the possibility to identify the MG as a distinct power system in the distribution system; 2) the local MG control of the relative resources; 3) the MG operative modes connected to the main grid [23] or in islanded conditions [8].

In detail, DC MGs can be managed to fulfill their own energetic needs (islanded mode) or to operate in grid connected mode. The "direct" interconnection of DC generators, storage and absorption systems to a DC bus could generate benefits both to MV and LV distribution, avoiding DC/AC conversion stage and the relative losses. DC MGs can also activate internal systems operative modes to provide Ancillary Services (AS) to the external AC grid. Power management, fault ride through, islanding detection and virtual inertia injection/absorption strategies are proposed [13,21].

A typical DC microgrids schematic representation is reported in Fig.3.

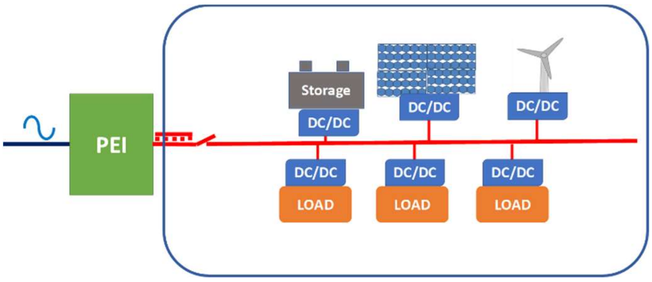

Fig 3 PEI-MG schematic representation

The considered DC MG is characterized by DC-DC interfaces connecting generation, load and storage systems to the MG bus. Furthermore, a bidirectional Power Energy Interface (PEI) carries out the suitable connection and conversion among the DC and AC grids.

In the proposed solution, the storage (or hybrid storage) converters is suitably equipped with an on-board controller acting as the MG Master controller. It receives data and commands from the PEI. In addition, it can communicate with the other DC-DC converters (Slaves) inside the MG to continuously guarantee the power management and balance both in grid-connected and in grid-off operative modes.

4. DC MGS AND VIRTUAL INERTIA

In this study the attention is focused on DC MGs role in RoCoF mitigation and in virtual inertia provision. The novel contribution is based on a dual approach constituted by preventing and solving actions to face instabilities events.

Preventive actions aim to "embed" a suitable amount of VERs generation in DC MGs to locally manage it in cooperation with DC loads and storage systems schedule, as above reported.

In this case, the great VERs energy production, necessary to favor the energetic transition, will not be straightly injected in AC grids. In fact, Master-Slaves controllers and the continuous communication with PEI converter permit to suitably manage the DC MG operative modes (grid connected and islanded modes).

Furthermore, solving actions can be ordered in case of AC grid needs. In such conditions, the PEI converter can request DC MGs intervention to provide their virtual inertia.

4.1 Dual approach: preventive actions

The "preventive" step of the proposed dual approach is based on the preliminary analysis of a specific grid. In case of a Low Voltage (LV) grid, connected residential/industrial loads, their absorption data and graph have to be considered. In addition, worst operative conditions for the specific LV grid and annual VERs production graph for the chosen installation site have to be jointly analyzed with data relative to previously connected VES plants. The implementation of a suitable code permits to define how many and which DC MGs operate in grid connected in island mode in a considered context.

To better understand the above-mentioned approach, some real case studies are analyzed. The total inertia mass M and RoCoF represent meaningful Key Performance Indicators (KPIs) to characterize grid frequency stability [24].

4.1.1 Scenario 0

In the following energetic generation and load conditions are reported for a typical Italian city (Scenario 0). Conventional and RES systems characterize Turin power generation panorama as reported in Table 1 [25] and Fig.4 referring to 2019 provisional data.

Furthermore, a typical daily load profile is shown in Fig. 5.

Table 1 Generation data

Actual Generation Data per Source Type [GWh]				
Solar	**Wind**	**Hydro**	**Thermo**	**TOTAL**
1,728	**0,030**	**11,013**	**23,823**	**36,594**

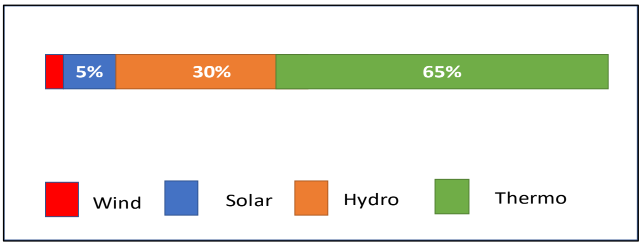

Fig 4 Percentage of generation Data per Source Type

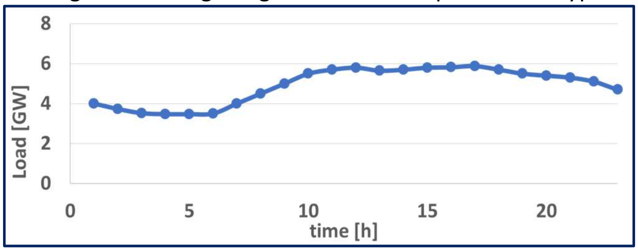

Fig 5 Typical daily load profile

As reported in Fig.5 the considered power system has to satisfy hourly load needs included in the range (3470-5880) MW.

Preliminary KPIs evaluation for the above-mentioned scenario was carried out in case of 16.6 MW generation loss. The obtained M and RoCoF results are reported in Eq.3 and Eq.4 respectively.

$$M = \sum M_i = \frac{1169\ MW*s}{Hz} \quad (3)$$

$$RoCoF = \frac{df}{dt} = \frac{-16.6MW*Hz}{1169\ MW*s} = \frac{-14.26mHz}{s} \quad (4)$$

4.1.2 Scenario 1

In the same context, Scenario 1 is characterized by VER sources (such as PV and wind generations) fulfilling 25% of daily maximum load. In this case, DC and AC loads are connected by suitable interfaces to the main AC grid.

In detail, 1.47 GW VER generation is introduced in the main grid and synchronous generation declines to 2.42 GW. In Table 2 VERs data, calculated inertia constant of the machine M and RoCoF values in the Scenario I conditions are reported.

It is worth noting the 25% load fulfilment by PV and wind generations causes the inertia constant of the machine MSC_1 decrease of about 38% and the $RoCoF_1$ absolute value increase of about 60%.

Table 2 Scenario 1 results

VES	**25%**
MSC1 [MW*s/Hz]	**727.90**
RoCoF1 [mHz/s]	**-22.89**

4.1.3 Scenario 2

Scenario 2 is determined considering the following question: which is the adequate energy amount to inject in the specific grid to both guarantee energetic need satisfaction and “prevent” frequency critical conditions?

Analyzing the above-mentioned information and the Italian Regulatory Authority for Electricity and Gas of the Distribution (ARERA) data set [26] the implemented code defines to take advantages of 75% residential loads to realize DC MGs including VER generation and normally working in islanded mode.

Generally (not COV-19 conditions), residential loads are characterized by low consumption during the day when PV generation can assure high performances. Therefore, if injected into the main grid, the produced energy could cause criticalities. DC MGs including residential loads and storage could be suitably supplied by means of these VERs plants.

Furthermore, the remaining VERs production can be connected to AC network and they can contribute to fulfill industrial loads. The obtained results are reported in Table 3.

Table 3 Scenario 2 results

%VER	**25%**
VER_AC_grid [GW]	**0.37**
VER_DC_MGs [GW]	**1.10**
MSC3 [MW*s/Hz]	**1058.65**
RoCoF3 [mHz/s]	**-15.74**

A comparative analysis between the above-mentioned Scenarios 0, 1 and 2 underlines KPIs improvements by the introduction of wind and PV energy in DC MGs, suitably connected to the AC grid by Power Energy Interface (PEI) systems. Obtained results report total inertia and frequency variation values comparable to VER free context as in Scenario 0 and far enough to Scenario 1 KPIs.

It is worth noting the same process is carried out for different values of generation loss and for different VERs percentage fulfilling load consumption.

Obtained results demonstrate DC MGs can represent promising solutions to mitigate frequency stability problems avoiding heavy intermittent RES penetration in the AC grid.

4.2 Dual approach: solving actions

In addition to frequency instabilities mitigation, grid connected DC MGs can be suitably configured and controlled to provide virtual inertia service to the main AC grid. In this paper a novel strategy is proposed. It consists in the implementation of a coordinated emulated inertia control logic taking advantage of involved power electronic converters.

Considering the DC MG architecture shown in Fig. 6, the Master controller is also able to organize and activate intervention actions to respond to requests from the AC network.

On the base of its continuous scheduling activity, the storage Master controller periodically sends data packet to the PEI converter to communicate the available power to participate to virtual inertia service. In case of load variation in the AC grid causing frequency instability [27, 10], the PEI is aware of the underlying MG (MGs) availability to participate to virtual inertia control by periodically received data packets. In that condition, the MG can activate its storage systems charge operations or its loads absorption fulfilment in response to AC grid requests.

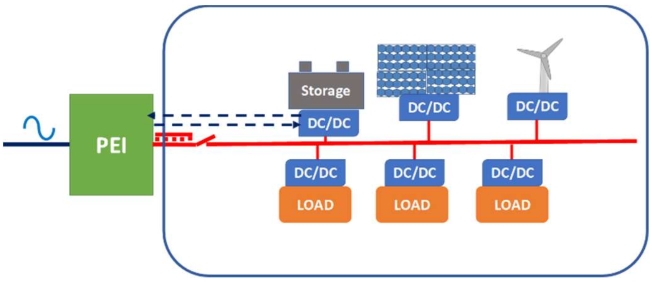

Fig 6 PEI-Storage virtual inertia service to AC frequency regulation

The proposed solving actions are going to be validated in the next months.

5. CONCLUSION

This document focuses on frequency instabilities caused by deep penetration of Inertia Free RES in AC grids (2030 scenarios). DC MGs involvement in the considered energetic context is proposed. DC MGs can contribute to mitigate frequency instability events. The proposed approach aims to “embed” suitable VERS amount in islanded DC MGs locally managing them. In addition, available DC MGs can work as Virtual Service provider on AC grid request. The propose dual approach is applied to an Italian city. Future energetic scenarios are considered and the relative KPIs are calculated according to the proposed strategy.

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