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A Simulation Analysis for Assessing the Reliability of AC/DC Hybrid Microgrids – Part I: Underground Station and Car Parking

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***Abstract*—This paper reports the results of a simulation study with the aim of evaluating the capability of two portions of a hybrid AC/DC MV/LV network of maintaining their operation in off-grid mode during the loss of the main AC grid due to a failure. In particular, the study aims to verify, in the case of islanded operation of the two microgrids, the continuity of the electricity service by exploiting the local generation plants, Energy Storage Systems (ESSs), and other flexible resources managed by suitable algorithms in different energy scenarios. The analysis was carried out considering two microgrids: an underground station and a car parking with Electric Vehicles (EVs). For assessing the performance of the network, specific indicators have been defined and calculated.**

Keywords—AC/DC microgrids; continuity; security; reliability; flexibility.

I. Introduction

In the last decade, the scientific community has demonstrated an increasing interest in the concept of DC and hybrid AC/DC microgrids.

In [1], the authors present an exhaustive review of the power architectures, applications, and standardization issues for DC microgrids. In [2], the control strategies and stabilization techniques of such kinds of microgrids are analyzed. Also in [3], the authors face the problem of voltage control and energy management strategy of active distribution systems with a grid-connected DC microgrid as well as for an islanded DC microgrid with hybrid energy resources. In [4], an application of multilevel DC microgrids to residential buildings is presented, showing a method for optimizing the efficiency of DC/DC converters in parallel. In [5], a new and more flexible architecture for hybrid AC/DC microgrids with a multiport interlinking converter is proposed. Finally, in [6], a solar photovoltaic-battery energy storage-based microgrid with a multifunctional voltage source converter is presented. The above-cited papers represent only a small sample of the wide recent literature on the topic.

According to a meaningful increase in reliability and availability of the networks in both customer and operators point of view, one interesting aspect of hybrid AC/DC and DC microgrids is to investigate their reliability and their capability of ensuring service continuity in case of loss of the main AC supply. With this aim, the project "2.7 Modelli e strumenti per incrementare l'efficienza energetica nel ciclo di produzione, trasporto, distribuzione dell'elettricità", in the framework of the Research on Power Systems PTR 2019-2021 program, is currently examining various microgrids in order to collect useful information on these aspects. Considering previous studies and this paper, one topic appearing worthy to be investigated is how local generators, especially those based on Renewable Energy Sources (RES), ESSs, both stationary and for mobility, and flexible resources can contribute to the islanded operation of specific hybrid AC/DC microgrids.

In particular, in this paper, the authors analyze the impact of different energy scenarios on two hybrid networks: an underground station and a car parking with charging stations for EVs, in terms of the possibility of maintaining the continuity of supply for a given time. It is worth underlying that the study considers a very particular case: microgrids, operating in island mode due to a fault, are not equipped with specific devices for emergency power supply. What the study wants to investigate is, if it is possible and under such hypotheses, maintaining a microgrid with specific features in operation mode during a fault with only its local resources, and increasing the reliability for power supply of its loads. the second challenge that this study aims to address is: an increase in the number of RESs and ESSs can impact the results of such an analysis. Indeed, greater penetration of generating plants that exploit RESs, but also controllable loads, storage systems, and devices that are capable of implementing demand response actions, are expected in the next decades.

In [6], the authors investigated experimentally the feasibility of a smooth transition from grid-connected to stand-alone mode of a microgrid via a suitable control algorithms and presented a simple case with a storage system and a PV system. The present study investigates the possibility of such a transition from an energy point of view. As a first step, five different energy scenarios are defined based on the last reports of Terna, WEC, REN21, ENTSO-E, and other prominent organizations [7]-[11]. Then, four different microgrids are chosen and analyzed, showing the different behavior depending on the flexible resources and generators available: Photovoltaic (PV) and wind generators, controllable loads, static storage units, EVs and charging stations using V2G technology. Finally, some indicators defined by the same authors are calculated for assessing the reliability of each microgrid during a specific fault event.

The four microgrids considered in this study are: an underground station; a car parking with EV charging stations; a residential area downstream a distribution substation; a port area. In this paper, the first two areas are examined while the residential area and the port area are discussed in [12].

II. The Hybrid AC/DC Microgrids

The hybrid network of the Underground station (Fig. 1) is supplied by a 20 kilo volts AC grid and characterized by various voltage levels. An AC/DC converter provides DC supply to the traction services; a MV/LV transformer supplies

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the 400 volts bus for the underground station services; a further AC/DC converter allows the supply of DC loads and the connection of a PV plant and storage units. The loads in the microgrid is comprised of lighting, ventilation, air conditioning, shops, etc.

The second microgrid, represented in Fig. 2, is that of a car parking. The grid is supplied by the public 20 kilo volts distribution grid by an MV/LV transformer. It has some AC loads (lighting, security point, video surveillance, electric gate, external lighting, etc.), and a DC bust connecting fast-charging stations for EVs, a PV system, and an energy storage system. The daily production profiles of the PV plants in the microgrids, expressed in p.u. of the rated power, are shown in Fig. 3. For their construction, the historical production data for the Italian territory in 2020 were considered [11]. The generation profile, on an hourly basis, of the individual generators present in the two microgrids were then obtained by defining the rated power of the generators for each scenario multiplied by the profiles in Fig. 3.

The size of the stationary ESS was estimated by applying the following steps;

- 1st Step: the base energy scenario (2020) is considered, and the daily production and consumption profiles are defined for each area. While the production profile is calculated as described above, and the daily consumption profiles are estimated from previous studies for each case study;
- 2nd Step: the difference between generation and consumption is calculated. The production/consumption profiles are built on a quarter-hour basis and, consequently, the different will appear as a row vector, called “difference vector”, consisting of 96 elements indicative of the average difference between the two profiles (production and consumption) for each 15 minutes-time interval;
- 3rd Step: the minimum value of the difference vector is found;
- 4th Step: the size of the static storage system is calculated considering the commercial size immediately higher than the minimum value extracted from the difference vector and increased by 30%; the capacity of the battery is calculated assuming type 2C batteries.

The above procedure for calculating the rated power and capacity of the energy storage was necessary because in all the energy scenarios deduced from the examined reports, although storage systems installation trend is clearly declared in constant increase, it seems never reaching values suitable for the aim of this study. The above-described procedure appeared to be a good compromise for increasing the power and capacity of the storage units present in the microgrid, and at the same time, maintain these quantities far from those that would have characterized a storage system working as an emergency power supply.

Regarding the load, for the underground station, the load profile (Fig. 4) for each month were obtained by the study presented in [13], where the authors carry out a monthly-based evaluation of the energy consumption of an underground station with an extension of approximately 3000 m^2 and an annual influx of approximately 5.3 million passengers. The profiles shown in Fig. 4 only considers the electricity consumption attributable to the typical systems present in a station, such as: lighting, air conditioning, ventilation, video surveillance, etc., neglecting the consumption of the section devoted to the electric traction, since this was assumed to be supplied by the other underground station of the same line.

On the other hand, regarding the car parking, once the typical systems present in this area were defined (for example public lighting, signaling and video surveillance systems, etc.) an analysis of the charging profile was carried out considering typical occupancy profiles varying with seasons and the days of the week (weekdays and weekend); therefor, the charging profile of EVs is illustrated in Fig. 5. For the recharging section, to represent a more realistic condition with regards to the number of EVs connected to the electricity network, the study in [14] presents a percentage estimation for EVs connected to the grid during the different hours of a day.

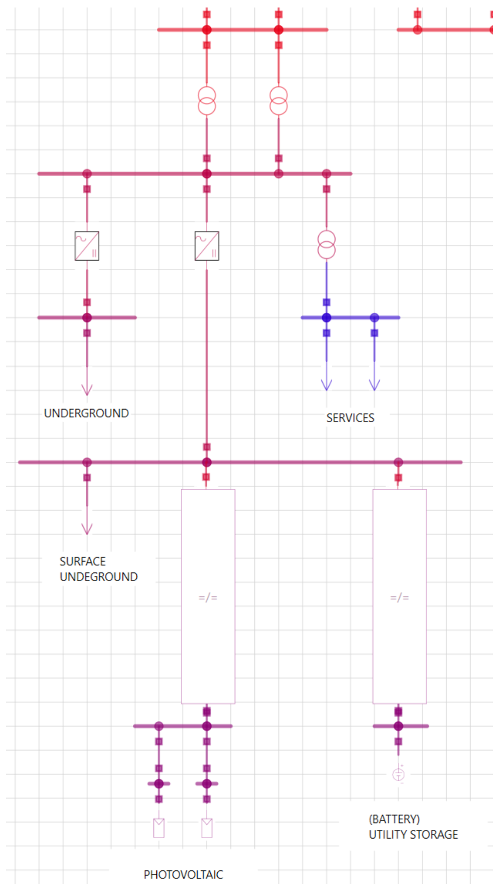

Fig. 1. Hybrid AC/DC microgrid of the underground station.

According to the methodology described for calculating the features of the storage units, Fig. 6 and Fig. 7 show the daily trends of generation, consumption and the different vector for the underground station and car parking respectively, referred to the 2020 energy scenario, characterized by a lower penetration of distributed resources. In this energy scenario, the capacity of the static storage system was determined equal to 500 kWh for the metropolitan area and 25 kWh for the car parking area.

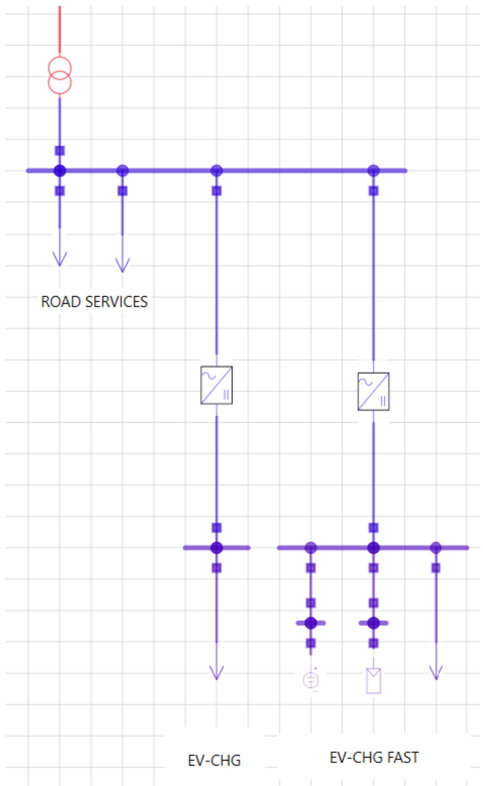

Fig. 2. Fig. 2. Hybrid AC / DC network of the Parking Area

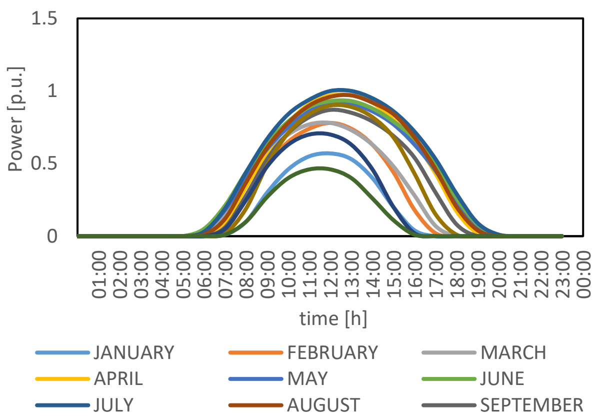

Fig. 3. Average monthly photovoltaic production in per unit (p.u).

Starting from the data reported in [7]-[10], finally, the scenarios for the simulations are defined (Table I and Table II) for both microgrids. Scenario 2020 is the base scenario. Scenarios 2030BC and 2030DEC are two different projections of the energy scenario in 2030, based on the analysis made by Terna and Snam [9]. Analogously two different future scenarios for 2040 are defined.

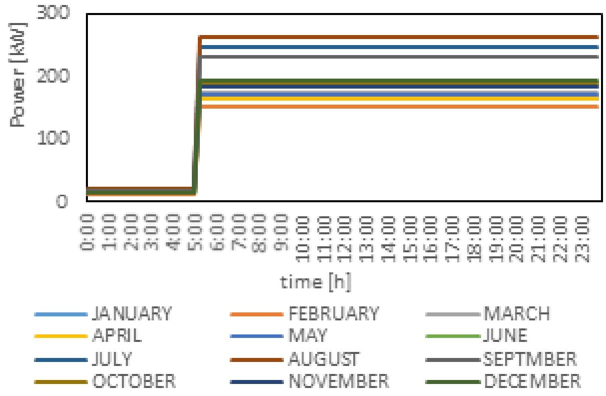

Fig. 4. Daily load profile of the underground station.

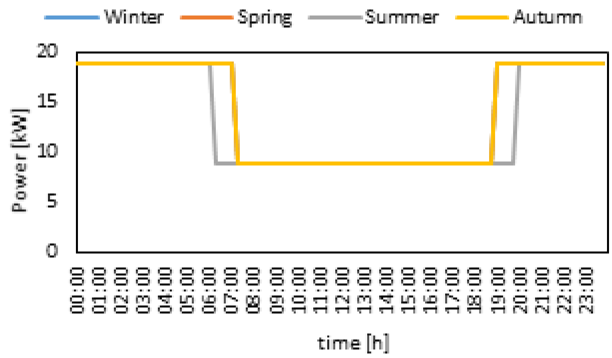

Fig. 5. Typical EVs' daily charging profile in the car parking for various seasons, variable consumption of EVs is excluded.

III. METHODOLOGY

The methodology implemented to assess the reliability of hybrid AC/DC microgrids is the following.

Firstly, it is assumed that a failure event occurs, causing the loss of supply from the main grid, and finally leads to operation of the microgrid in islanded mode. According to the last data from the Italian Regulatory Authority for Energy, Networks and the Environment (ARERA), the average duration of the fault is assumed 45 minutes [15].

By a Monte Carlo-like approach, the time interval in which the fault occurs is randomly drawn within the 96 15 minutes-time intervals of the day. Similarly, months of the year and days of the week are drawn.

On the basis of this information (months, days of the week, time in which the fault occurs) the daily load profiles and the daily production profile of the PV system to be used in the simulations are selected within those available. In presence of storage units and EVs, the number and type of EVs (V1G or V2G) and the State of Charge (SoC) of all the batteries are drawn too. Particular attention has been paid to the SoC of the EVs' batteries for which the probability of being in charging at a given time of the day must be taken into account [14].

As soon as all the data of the system are known, it is assumed that all flexible resources and generators are managed by the energy management system of the microgrids to maximize the time for which the microgrids can operate in islanded mode. For doing this:

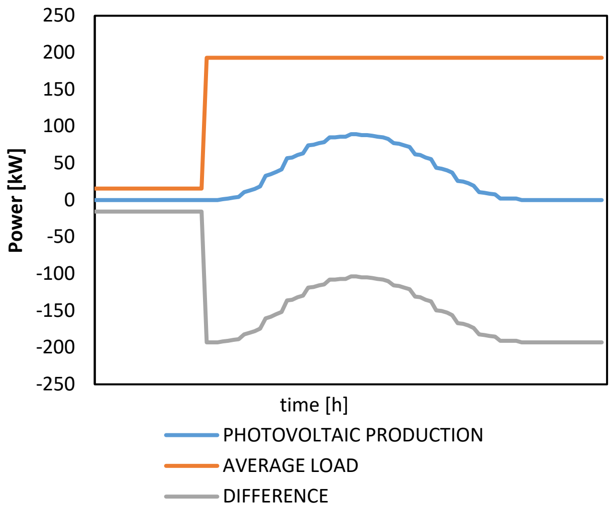

Fig. 6. Average profile of load, production and energy balance of the underground station in the 2020 energy scenario.

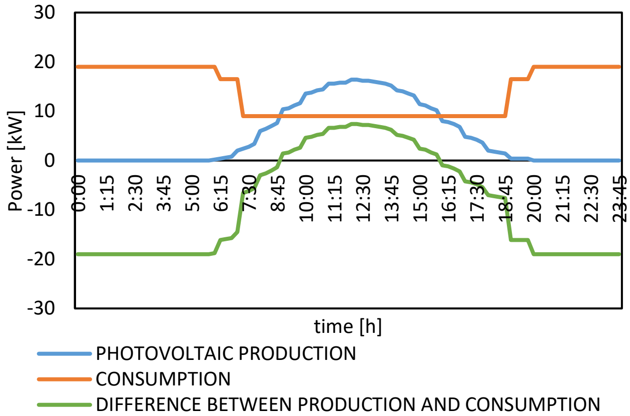

Fig. 7. Average profile of load, production and energy balance of the car parking in the 2020 energy scenario.

TABLE I. UNDERGROUND STATION: ENERGY SCENARIOS

	SCENARIO				
	2020	**2030 BC**	**2030 DEC**	**2040 BC**	**2040 DEC**
Daily energy consumption [kWh]	3694	3694	3694	3694	3694
PV system rated power [kW]	109	130	170	175	175
Electric energy storage rated power [kW]	250	250	250	250	250
Electric energy storage capacity [kWh]	500	500	500	500	500

TABLE II. CAR PARKING: ENERGY SCENARIOS

	SCENARIO				
	2020	**2030 BC**	**2030 DEC**	**2040 BC**	**2040 DEC**
Daily energy consumption [kWh]	653.5	973.5	973.5	1993	1993
PV system rated power [kW]	20	35	45	90	120
Electric energy storage rated power [kW]	25	25	25	25	25
Electric energy storage capacity [kWh]	50	50	50	50	50
V1G EV [n]	5	10	10	25	25
V2G EV [n]	5	10	10	25	25

- generators are controlled in order to regulate voltage and frequency and supply the load;
- battery storage systems can behave as generators or loads depending on the difference between production and consumption in the microgrid. The SoC must be always included in the range 10%-90%, outside this range the battery enters the stand-by mode;
- interruptible loads are disconnected;
- flexible loads are shifted in time if generators are not able to supply the other loads. V2G EVs are considered as modulable loads/generators if the SoC allows the implementation of supporting the microgrid during the islanded operation, while V1G EVs are considered interruptible loads, if necessary,

In the various energy scenarios, the above quantities are present with different entities, and this influences the outcome of the assessment. Therefore, a system which is not able to maintain the stand-alone operation in the 2020 scenario could be able to do it in the 2040DEC.

Since the instant in which the fault influences the difference between production and consumption, the number of EVs connected to the grid and their SoC, and the other parameters impacting the assessment, various simulations must be carried out and the most significant one must be identified in order to clearly describe the behavior of the stand-alone system.

For doing this, the two networks were simulated in Matlab/Simulink environment together with the control algorithms for loads, generators, and storage units.

IV. RESULTS OF THE SIMULATIONS

A large number of simulations was done for the two microgrids. Three simulations have been chosen for each microgrid based on the rate between production and generation and on the presence of flexible resources. For the three simulations, table III indicates the capability of each microgrids to ensure operating in islanded mode during a 45-minute fault event: number 1 marks microgrids are able to operate in off-grid mode, and number 0 means they can not have a reliable operation during the fault event.

Table III reports only two cases for the underground station microgrid: 2020 and 2040DEC. The results for the other scenarios are not present since all scenarios for this microgrid are quite similar in which the microgrid may not operate in off-grid mode after the fault event (binary variable is 0). Below two examples of calculation are reported, followed by the calculation of some general indicators for assessing the behavior of the microgrids. Fig. 8 shows the results of one of the simulations carried out for the underground station microgrid. The loss of supply occurs at 18:00 and lasts 45 minutes. During this time range, the photovoltaic system present in the area produces a low amount of energy and is unable to guarantee the energy demand. The storage system delivers energy in the first 30 minutes before discharging. Because batteries in ESSs are able to supply only for 30 minutes, after 18:30 operator have to start shedding loads sharply. Therefore, the microgrid is no more able to preserve its off-grid operation mode.

TABLE III. OUTCOMES OF THE SIMULATION

	UNDERGROUND STATION			***CAR PARKING***		
	S1	***S2***	***S3***	***S1***	***S2***	***S3***
2020	0	0	1	1	0	1
2030BC	-	-	-	1	1	1
2030DEC	-	-	-	1	0	1
2040BC	1	0	0	1	1	1
2040DEC				1	1	1

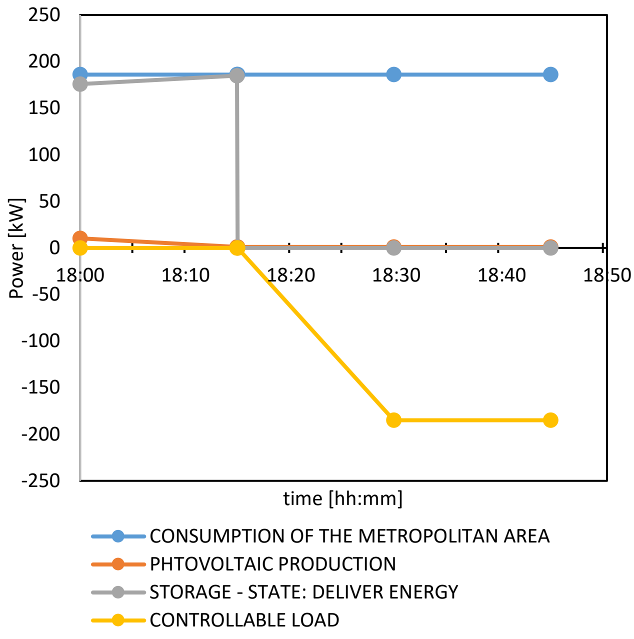

Fig. 8. Underground station: simulation results - Scenario 2020.

Fig. 9, analouglsy, shows the results of one of the simulations regarding the car parking microgrid during a loss of the main AC grid. The fault occurs in the MV network at 18:15. at 30-minutes duration of the fault, both PV system and ESS supply the demand electric power. at 18:40 batteries are depleted, and PV system is not able to generate enough power. this is the point where V2G EVs start delivering energy to the loads and compensate shortage power. therefore, in such circumstance, only V2G EVs can help in keeping the microgrid in stand-alone mode.

To quantify the reliability of the hybrid networks, some indicators have been defined. The first set of indicators is used for characterizing the microgrids in the various energy scenarios and during the failure event as follows:

- the *RES indicator* which evaluates the percentage of generation from renewable sources P_{RES} compared to the total power consumed in the examined area P_{load}:

$$\dot{RES} = \frac{P_{RES}}{P_{load}} \cdot 100 \tag{1}$$

- the *FLEX indicator* that evaluates the flexibility of the load, i.e. the amount of energy that can participate at demand response (load shedding for example) $P_{LOAD,FLEX}$ divided by the total load:

$$FLEX = \frac{P_{load,flex}}{P_{load}} \cdot 100 \tag{2}$$

- the *BESS indicator* which evaluates the rate between the power supplied by the storage systems P_{BESS} and the total power consumed in the examined area:

$$\dot{BESS} = \frac{P_{BESS}}{P_{load}} \cdot 100 \tag{3}$$

Another set of indicators was defined to quantify the impact that the individual energy scenarios have on the

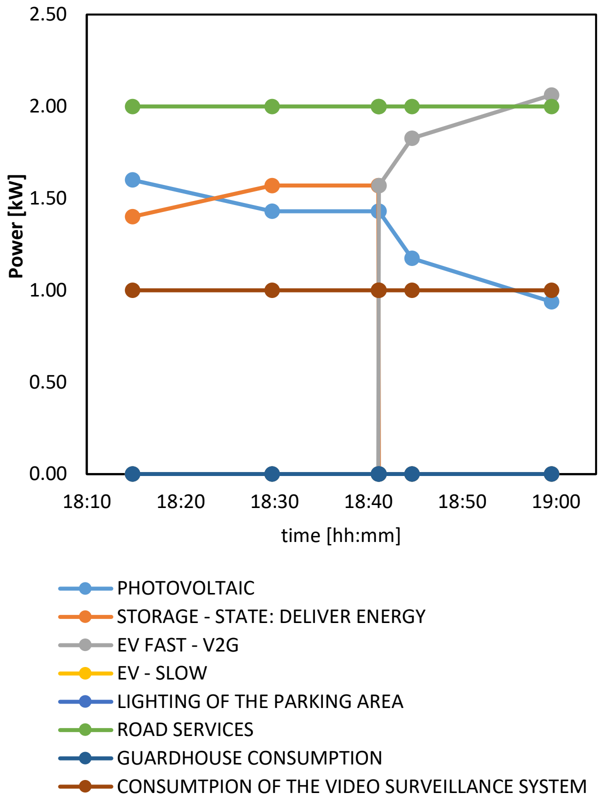

Fig. 9. Car Parking: simulation results - Scenario 2020.

safety of the electricity network examined. The first indicator is defined as "the autonomy index of the microgrid" which quantifies the islanding capacity of the microgrid upon the occurrence of a fault event. It is given by the rate between the duration of the stand-alone operation and the fault duration:

$$i_1 = \frac{h_i}{T} \cdot 100 \tag{4}$$

The second indicator is the "*flexibility index*" which quantifies the variation (increasing or decreasing) of active power available at the connection point between the islanded microgrid and the main network. It is given by:

$$i_2 = \frac{\Delta P_{load.flex} + \Delta P_{RES} + \Delta P_{BESS}}{A_n} \cdot 100 \tag{5}$$

where An is the rated power of the transformer at the point of common coupling between the two grids, and ΔP_{RES}, $\Delta P_{load.flex}$ and ΔP_{BESS} are, respectively, the average variation, during the fault, of the power generated by all RES plants, of the flexible load demand, and of the power delivered or consumed by the storage systems in the microgrid.

The last indicator is defined as "*the power profile modulation capacity index*" which evaluates the energy $\Delta E_{flex(T)}$ supplied by all the flexible resources present in the examined area compared to that theoretically available to keep the AC/DC network in stand-alone mode following the occurrence of the fault (E_{th}):

$$i_3 = \frac{\Delta E_{flex(T)}}{E_{th}} \cdot 100 \tag{6}$$

Table IV and V reports the calculation of the six indicators for the underground station and the car parking microgrids for the three most representative simulations.

TABLE IV. UNDERGROUND STATION: INDICATORS

SCENARIO 2020						
	$R\dot{E}S$	$FLEX$	$B\dot{E}SS$	i_1	i_2	i_3
1	2 %	50 %	48 %	33 %	47 %	49 %
2	1 %	99 %	0 %	0 %	41 %	0 %
3	65 %	0 %	35 %	100 %	41 %	100 %
SCENARIO 2040DEC						
	RĖS	FLEX	BĖSS	i_1	i_2	i_3
1	0 %	0 %	100 %	100 %	46 %	100 %
2	0 %	50 %	50 %	33 %	3 %	50 %
3	90 %	10 %	0 %	0 %	42 %	0 %

TABLE V. CAR PARKING: INDICATORS

SCENARIO 2020						
	$R\dot{E}S$	$FLEX$	$B\dot{E}SS$	i_1	i_2	i_3
1	36 %	37 %	44 %	100 %	2 %	100 %
2	4 %	45 %	25 %	0 %	3 %	61 %
3	100 %	57 %	0 %	100 %	4 %	100 %
SCENARIO 2030BC						
	$R\dot{E}S$	$FLEX$	$B\dot{E}SS$	i_1	i_2	i_3
1	178 %	24 %	0 %	100 %	8 %	100 %
2	2 %	37 %	98 %	100 %	7 %	100 %
3	0 %	11 %	100 %	100 %	2 %	100 %
SCENARIO 2030DEC						
	$R\dot{E}S$	$FLEX$	$B\dot{E}SS$	i_1	i_2	i_3
1	0 %	28 %	100 %	100 %	10 %	100 %
2	234 %	4 %	0 %	67 %	9 %	100 %
3	47 %	18 %	32 %	100 %	2%	100 %
SCENARIO 2040BC						
	$R\dot{E}S$	$FLEX$	$B\dot{E}SS$	i_1	i_2	i_3
1	0 %	28 %	100 %	100 %	22 %	100 %
2	137 %	30 %	0 %	100 %	20 %	100 %
3	0 %	21 %	100 %	100 %	12 %	100 %
SCENARIO 2040DEC						
	$R\dot{E}S$	$FLEX$	$B\dot{E}SS$	i_1	i_2	i_3
1	100 %	17 %	0 %	100 %	13 %	100 %
2	158 %	50 %	0 %	100 %	20 %	100 %
3	0 %	24 %	100 %	100 %	17 %	100 %

By comparing the values assumed by the indicators of the first set with the capacity of the grid to operate in standalone mode for 45 minutes (results in Table III), it can be stated that the values of these indicators give precious indications on the flexible resources of the microgrids but they can't be put in relation with its reliability and with the continuity of the service.

The i_1 index has very variable values for all the simulations since it depends on the instant at which the fault occurs, the SoC of the batteries and, in general, the resources of the network. The car parking microgrid shows higher values of this indicator for almost all simulations. This is due to the lower load and to its low variability in time. The same analysis can't be said for the underground station.

i_2 is, in general, quite low (from 2% to 22%) and this indicates that in realistic scenarios like those considered in this work, the power variation at the point of common coupling is, in general, not significant.

Finally, i_3 is always high, showing that the considered microgrids can contribute to the main grid needs by modifying their consumption and increasing the grid reliability.

V. CONCLUSION

This work has presented a simulation analysis of the reliability of two microgrids investigating how the presence of flexible resources and local generators can increase the possibility of operating in stand-alone mode in case of loss of the main grid. Two sets of indicators have been calculated: the first one for characterizing the microgrid with regards to the presence of storage, flexible load, and RES generators, the second one for assessing its reliability. In general, it can be concluded that, in realistic scenarios based on the elaboration of the most recent projections of prominent energy and electrical organization, distributed flexible resources seems not to be able to support solely the operation of hybrid microgrids for more than 15-30 minutes (as an average), that is less than the average failure recovery time for Italian networks.

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