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ANALYSIS OF FAILURE RATES OF AC AND DC MICRO-GRIDS

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***Abstract* - Nowadays dc distribution is gaining importance, as an increasing amount of loads is natively biased in dc. In addition, dc micro-grids are usually characterized by high efficiency and simple design. Moreover, they can better accommodate renewable generation and storage systems. These are the main benefits attributed to dc distribution grids. Reliability aspects, usually, are not sufficiently taken into account.**

This paper describes an initial methodological approach to compare (in both analytic and numerical way) ac and dc micro-grids. In particular, the analysis has been focused on the effects on loads of main supply interruptions. The performed analysis showed that dc micro-grids have a higher immunity to these events than that displayed by ac micro-grids. On the other hand, the front-end converter (FEC) interfacing ac main supply and dc micro-grid is a single point failure for the whole system. The paper describes (and analyses) some technical solutions to reduce the effect of FEC failure on loads. Moreover, the signals and alarms that should be used in order to maximize the obtained quality-of-service levels are reported, along with some diagnostic considerations.

NOMENCLATURE

λ^{ac}	failure rate of load supply for dc micro-grid
$\lambda_{\mathrm{ac/dc}}$	failure rate of an ac/dc converter
$\lambda_{\mathrm{bridge}}$	failure rate of a thyristor rectifying bridge converter
λ^{dc}	failure rate of load supply for dc micro-grid
$\lambda_{\mathrm{dc/dc}}$	failure rate of a dc/dc converter
λ_{FEC}	failure rate of a FEC
λ_{int}	failure rate of the main supply
λ_{STG}	failure rate of the storage device
τ	minimum time required by ac micro-grid to detect an interruption, disconnect from main grid and start to be fed by ESS
t_{int}	duration of the main supply interruption
$(\cdot)\big\|_{\mathrm{wESS}}$	subscript indicating that the quantity $(\cdot)$ has been evaluated when the ESS is available
$(\cdot)\big\|_{\mathrm{w/oESS}}$	subscript indicating that the quantity $(\cdot)$ has been evaluated when the ESS is unavailable
FEC	IGBT front-end converter
ESS	energy storage system
PV	photovoltaic source

1. INTRODUCTION

Distribution grids (both private and public ones) are experiencing significant modifications due to a vast variety of reasons [1].

A first aspect is related to the widespread diffusion of distributed generation at medium and low voltage levels. They are usually located near loads and are somewhat replacing (or at least competing with) traditional (large) generation plants, which, are located far from customers. This trend is mainly due to the increasing need for greener and more sustainable energy sources (such as wind and solar) in order to reduce carbon footprint. The transition from passive to active power distribution networks, along with the stochastic behavior of renewable energy sources, can lead, if not properly dealt with, to a worsening of quality level of electric supply.

A second aspect is related to the demand for a high level of continuity of the power supply by a progressively increasing number of customers. For them, an interruption may represent a potentially harmful condition and may cause even significant damages.

These considerations call for the need of new management paradigms for micro-grids and customers. In particular, it is mandatory to coordinate (a potentially high number of) generators—even the smallest ones—and exchange information with loads in order to obtain the desired quality of supply and energy efficiency standards.

In order to achieve these results an adequate information infrastructure should be available. This facility could enable the fast and reliable exchange of a great amount of information and control signals among the various players.

The opportunities coming from the introduction of dc distribution grids are being studied in these years and are progressively considered a promising technical solution from industry [2–7]. There are many reasons for this. The first is related to the fact that the great majority of electronic equipment already operates in dc, but must be provided with an input rectifying stage since the current distribution system is ac. A second reason relates to distributed generators—

typically renewable energy sources—which, in fact, generates a dc voltage. The adoption of a dc distribution network would substantially allow for a simplification of the electronic converters currently installed with an expected increase of the continuity of supply. The present work is focused on this aspect. In particular, the paper addresses the comparison between ac and dc distribution micro-grids. The analysis starts from the assessment of the reliability indices and highlights how the adoption of dc islands, if properly designed, increase the quality of service.

The work is particularly focused on the identification of the most critical elements of the dc island and of the planning measures to achieve the quality improvement. The possibility of introducing a "distributed monitoring" of the various components in order to diagnose and prevent possible malfunctions is also analyzed. Starting from the results obtained in the first part of the work, different priority sets to achieve an adequate reduction of the failure rates of the mission of the micro-grid (i.e., load supply) are identified.

The paper is structured as follows. In Section II the main components of the two (ac and dc) micro-grids are described, along with the main assumptions and hypotheses at the basis of the present work. Section II also presents the evaluation of the failure rates of the load supply in the two cases. Section III presents the calculation of the failure rates associated to main supply interruptions and (only for dc micro-grid) FEC faults. Section IV contains some diagnostic considerations and identifies the principal signals and alarms that should be used in order to maximize the obtained quality-of-service levels. Finally, in Section V conclusions are drawn.

2. PROBLEM DEFINITION

In this Section a formal comparison between ac and dc distribution system is derived.

A. Hypotheses and general framework

In order to clearly define the scope of the present work, some hypotheses are needed. Two similar micro-grids are compared (as depicted in Fig. 1). They both provide the same service and are equipped with the same loads, generators and energy storage systems (ESSs), although one (Fig. 1(a)) is directly connected to the ac main distribution grids, while the other (Fig. 1(b)) is made up of a dc bus, connected to the main distribution grid by means of a front end converter (FEC). So, the mission of both micro-grids is identical, i.e., they both supply loads and accommodate ESS and a photovoltaic source (PV). The aim of this paper is to assess the reliability of supply in both cases and compare the obtained results (both in an analytic way, through formulae, and in a quantitative way, through numerical calculation on a realistic test case). This means that only faults of system components (i.e., converters, ESS, FEC) have been considered.

Thus, the present study will assess the effect of main supply interruptions on both micro-grids. To this end, some assumptions are needed in order to simplify calculations and obtain straight results.

Three different kinds of interruptions are considered [8]: i) transient interruptions ($t_{\mathrm{int}} \leq 1\,\mathrm{s}$); ii) short interruptions ($1\,\mathrm{s} < t_{\mathrm{int}} \leq 3\,\mathrm{min}$); and iii) long interruptions ($t_{\mathrm{int}} > 3\,\mathrm{min}$).

In all these aforementioned cases the ESS, if available, is supposed to be able to supply loads for the whole duration of the interruption. This may look like a potentially invalidating assumption but is, indeed, sound. In fact, the micro-grid is set to increase quality of supply and the installed ESS should be designed in order to enable some energy-intensive functionalities, such as peak shaving, load shifting, etc.. Thus, ESS's nominal energy is such that it can supply load during interruptions. Only for very long interruptions (usually greater than 20–30 min) energy stored in ESS could not be enough to supply loads. In these cases micro-grids should be equipped with a traditional generator. The presence of PV can only increase ESS back-up time during interruptions, thus procrastinating conventional generator's intervention. For this reason (and conservatively), PV will not be taken into account during the following calculations.

B. Effect of interruptions on load

Let λ_{int} be the failure rate of the main supply. Thus, λ_{int} has three different values according to the fact that transient, short or long interruptions are considered.

AC System

When an interruption occurs, the ac micro-grid would need a certain amount of time, τ, in order to disconnect from the main grid and start to be fed by the ESS. The minimum value for τ is the time needed to detect the voltage sag and to open the switchgear. An additional delay could be added to this time. This delay is related to the type of control implemented on the interface converter of the storage device.

If the ESS is not available (i.e., if it is faulted and is going to be restored) the interruption will completely pass to the load. Thus, the failure rate is

$$\begin{aligned}\lambda^{\mathrm{ac}}\big|_{\mathrm{w/oESS}} &= \lambda_{\mathrm{int}}\frac{\mathrm{MTTR}_{\mathrm{V_{ESS}}}}{\mathrm{MTBF}_{\mathrm{V_{ESS}}}} \\ &= \lambda_{\mathrm{int}}\mathrm{MTTR}_{\mathrm{V_{ESS}}}\left(\lambda_{\mathrm{STG}} + \lambda_{\mathrm{ac/dc}}\right),\end{aligned} \tag{1}$$

where $\mathrm{MTTR}_{\mathrm{V_{ESS}}}$ is the mean time to restore the full operation of the ESS (made up of both energy storage device and power converter) and $\mathrm{MTBF}_{\mathrm{V_{ESS}}}$ is the mean time between failures of the ESS (i.e., the sum of the failure rate of the ESS ac/dc converter $\lambda_{\mathrm{ac/dc}}$ and of the energy storage device λ_{STG}).

On the other hand, if the ESS is available, the ac micro-grid will suffer a transient interruption which lasts τ s. Af-

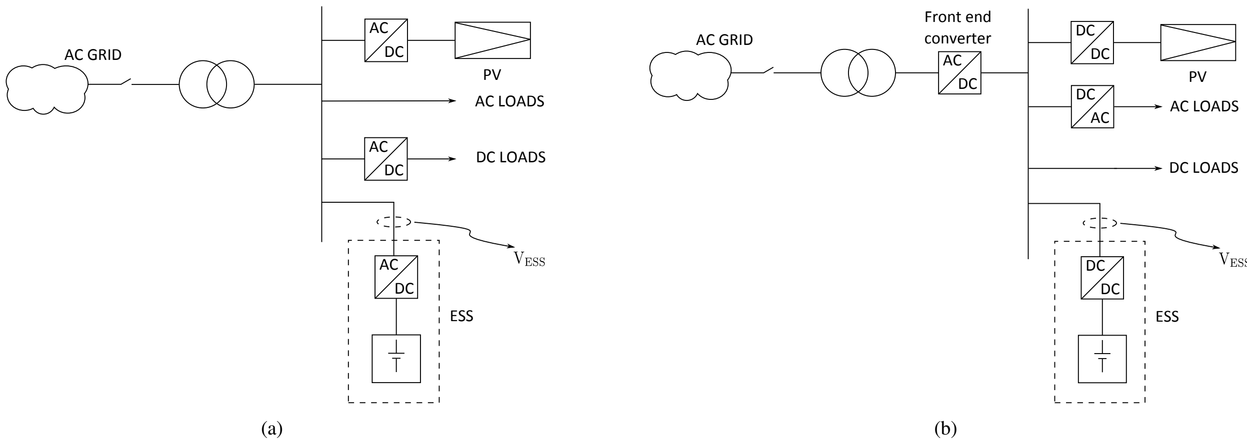

Fig. 1. Schematic representation of the two micro-grids analysed in the paper: (a) the ac micro-grid; and (b) the dc micro-grid.

ter the intervention of the main switchgear the micro-grid is supplied by the ESS. In this case the failure rate is

$$\lambda^{\mathrm{ac}}\big|_{\mathrm{wESS}} = \lambda_{\mathrm{int}} \left(1 - \frac{\mathrm{MTTR}_{\mathrm{V_{ESS}}}}{\mathrm{MTBF}_{\mathrm{V_{ESS}}}}\right). \tag{2}$$

The overall failure rate is given by the sum of (1) and (2) and is, as it could be expected,

$$\lambda^{\mathrm{ac}} = \lambda_{\mathrm{int}}. \tag{3}$$

This means that, in case of interruption the ac micro-grid experience an interruption: i), with a frequency $\lambda^{\mathrm{ac}}\big|_{\mathrm{w/oESS}}$, a transient one (lasting τ s) if the ESS is available; or ii), with a frequency $\lambda^{\mathrm{ac}}\big|_{\mathrm{wESS}}$, the same interruption experienced by the main grid.

DC System

In case of a dc micro-grid, the interruption will pass from the main grid only if the ESS is not available [9]. On the contrary, if the ESS is available, the micro-grid is decoupled from the main distribution grid and does not need any disconnection from the mains. In fact, the capacitors installed at the output stage of the FEC are enough to maintain the voltage of the dc bus at an acceptable level before the ESS starts to feed the load. Thus, the overall failure rate is

$$\begin{aligned} \lambda^{\mathrm{dc}} &= \lambda_{\mathrm{int}} \frac{\mathrm{MTTR}_{\mathrm{V_{ESS}}}}{\mathrm{MTBF}_{\mathrm{V_{ESS}}}} \\ &= \lambda_{\mathrm{int}} \mathrm{MTTR}_{\mathrm{V_{ESS}}} \left(\lambda_{\mathrm{STG}} + \lambda_{\mathrm{dc/dc}}\right). \end{aligned} \tag{4}$$

It is worth noting that the value obtained in (4) is different from that obtained in (1). In fact, usually, failure rates of dc/dc converters are lower than those of ac/dc converters such that

$$\lambda^{\mathrm{dc}} < \lambda^{\mathrm{ac}}\big|_{\mathrm{w/oESS}}. \tag{5}$$

It can be also verified that

$$\lambda^{\mathrm{dc}} \ll \lambda_{\mathrm{int}}. \tag{6}$$

C. Effect of FEC

The previous considerations about dc micro-grid do not take into account the fact that this grid experiences a permanent interruption when FEC breaks down (the rate according to which this happens being FEC failure rate λ_{FEC}). For this reason FEC can be regarded as a single-point failure.

Thus, suitable configurations and solution should be implemented in order to increase MTBF of the output supply of the FEC.

A first solution can be the total redundancy of the FEC. In this case the failure rate of FEC's dc output voltage is

$$\lambda_{V_{\mathrm{dc}}} = 2\lambda_{\mathrm{FEC}}^2 \mathrm{MTTR}_{\mathrm{FEC}}. \tag{7}$$

A possible improvement could be obtained using a stand-by full-power rated FEC. In this case failure rate would be

$$\lambda_{V_{\mathrm{dc}}} = \lambda_{\mathrm{FEC}}^2 \mathrm{MTTR}_{\mathrm{FEC}}. \tag{8}$$

In this equation, the doubling factor in (7) is missing, as the other FEC is not permanently active and, thus, thinking of it as an always-ready equipment is a reasonable assumption. In this way, failure rate of the dc supply is halved, at the expense of a transient perturbation caused by the delay in stand-by FEC intervention and of an increase in the overall costs. However, a way to avoid this two drawbacks is to replace the stand-by FEC by a traditional thyristor rectifying bridge. In this way costs are reduced and the insertion of the stand-by FEC in case of need is almost instantaneous. The drawback of this solution is the increase harmonic distortion of the currents during the (relatively short) operation of the bridge. It is also worth noting that the reliability of a thyristor bridge is greater than that of an IGBT FEC. This fact reduces the failure rate of the dc supply to:

$$\lambda_{V_{\mathrm{dc}}} = \lambda_{\mathrm{FEC}} \lambda_{\mathrm{bridge}} \mathrm{MTTR}_{\mathrm{FEC}}. \tag{9}$$

3. NUMERICAL CALCULATION

In order to numerically validate the whole study, the cases proposed in the previous Section are here analyzed in detail.

A. AC grid main supply failure rates

Data concerning ac grid main supply failure rates for year 2014 have been derived from Italian Regulation Authority's analysis of Distribution System Operators (DSOs) quality of supply [10]. This document provides, for three different sizes of distribution grids (Municipalities with more than 50000 residents, with a number of residents between 5000 and 50000, and with less than 5000 residents), data concerning the number of interruptions (transient, short, and long) per LV customer and the total number of LV customers. From these data, the value shown in Tab. 1 have been derived.

Table 1. Failure rate data for Italian LV distribution system.

		transient	short	long
$\lambda_{\text{int}}\ (=\lambda^{\text{ac}})$	$[10^{-3}\ \text{h}^{-1}]$	0.4792	0.1914	0.1671

B. Components failure rates

For what concerns failure rates of converters and storage device, many installed equipment (i.e., UPSs, and PV converters) have been analysed. This analysis has been performed during several years in order to verify the correspondence to technical specifications of the equipment provided to both public and private companies.

In order to perform the calculations each system has been divided in different reliability sub-assemblies. From the failure rate data of each component, the failure rates of each reliability sub-assembly have been calculated. Usually, the failure rate of each component is derived from Handbook-217Plus in "Ground" conditions and ambient temperature of $25\ ^\circ\text{C}$. Handbook-217Plus, which reports the prediction models of failure rates, developed by Reliability Information Analysis Center (RIAC), was created for the purpose of replacing the prediction method of failure rates MIL-HDBK-217 (reliability prediction of electronic equipment), not updated since 1995. However, MIL-HDBK-217 is still used when HDBK-217Plus does not have the prediction of the failure rate for the searched component. Failure rates for fans have been derived from NPRD-95 (non-electronic parts reliability data). Failure rates of energy storage device (made up of 198 series Lead-acid cells) have been derived from IEC 62380 or UTEC 80-810.

C. Comparison between ac and dc configurations

Using data in Tab. 2, the failure rates of the dc voltage due to interruptions from the main supply, as described in (4), can be calculated. The numerical values are reported in Tab. 3. It is worth recalling that failure rates of the load supply in case of ac micro-grid are those of the ac main supply, as reported in Tab. 1.

Table 2. Failure rates and MTTR values of micro-grid components.

$\lambda_{\text{dc/dc}}$	1.57	$[10^{-6}\ \text{h}^{-1}]$
$\lambda_{\text{ac/dc}} = \lambda_{\text{FEC}}$	3.15	
λ_{STG}	3.90	
λ_{bridge}	2.08	
$\text{MTTR}_{\text{V}_{\text{ESS}}} = \text{MTTR}_{\text{FEC}}$	8	[h]

Table 3. Failure rates of the dc voltage due to interruptions from the main supply in the case of a dc micro-grid.

		transient	short	long
λ^{dc}	$[10^{-7}\ \text{h}^{-1}]$	0.1982	0.0792	0.0691

It can be noticed that failure rates in case of dc micro-grid are significantly lower that those of the ac micro-grids. This is due to the fact that the interruptions on the main ac supply pass to the load in the latter case, while, on the other hand, are filtered by the FEC—only when ESS is available—in the former micro-grid configuration. Thus, when considering an ac micro-grid, an interruption (lasting τ or having the same duration of the interruption itself) could happen with the same frequency with which main grid interruptions occur. On the contrary, when considering dc micro-grids, only the interruptions that occur when ESS is not available do pass to the load and the frequency is four orders of magnitude smaller than that of ac micro-grids.

From Fig. 1 it can be noticed that dc loads in ac micro-grid and ac loads in dc micro-grid are connected by means of converters (ac/dc and dc/ac respectively). One may argue that this could increase failure rates for ac loads in the latter configuration, as two additional power-electronic-based equipment have been added. However, the total amount of dc and ac loads should be considered, in order to estimate the consequences of these modifications. In fact, even today a great number of loads operates (or can—almost effortlessly—operate) in dc (e.g., the great majority of white goods, hvac appiances, all electronics loads, etc.). The same values reported in Tab. 2 are used to calculate the failure rates of the dc voltage due to FEC faults in the different configurations, as described in (7)–(9), can be calculated. The obtained numerical values are reported in Tab. 4.

Table 4. Failure rates of the dc voltage due to FEC faults in the different configurations. TOT. RED.: with a totally redunded FEC; STAND-BY: with a stand-by FEC; BRIDGE: with a thyristor bridge.

		TOT. RED.	STAND-BY	BRIDGE
$\lambda_{V\text{dc}}$	$[10^{-10}\ \text{h}^{-1}]$	1.5876	0.7938	0.5242

4. DIAGNOSTIC CONSIDERATIONS

The assessments of the quality of supply in ac and dc islands performed and shown in the first part of the paper are valid under the assumption that the system components are provided with a proper diagnosis system. In particular, the electronic converters which are now playing—and will play in future—an important role in power systems, must be equipped with sensors able to promptly report anomalies as soon as they occur.

It can be said that the longer is the reporting time of fault condition (e.g., the fault of a cooling fan), the longer becomes the MTTR and, consequently, the higher becomes the frequency with which supply interruption of loads occurs. Thus, failure rate values calculated in the previous Section would not be valid any more.

In Appendix B the main variables to be monitored in order to obtained the described levels of reliability of the electronic converters are reported. It is especially useful to gather various diagnostic signals in relation to the severity of the dysfunction to be detected in order to correlate them with the failure rate used in the article. Four classes of alarms can be identified:

- **CLASS 1** alarms that enable to prevent future outages;
- **CLASS 2** alarms signalling a derating of the system;
- **CLASS 3** alarms signalling an outage of the system (i.e., converter break down)
- **CLASS 4** alarms signalling an intentional outage of the converters.

A complete description of these alarm classes is provided in Appendix A. These alarms are usually available for power converters diagnostic features.

In order to obtain these alarms, it is necessary to measure and monitor some electrical and environmental quantities. A list of these quantities is provided in Appendix B.

5. CONCLUSION

Starting from the values of main ac distribution grid failure rates, the comparison between ac and dc micro-grids has been performed.

The beneficial effects of dc distribution in terms of efficiency, converters design simplification, and simplification of the whole power system are already demonstrated in literature. These effects are such that dc distribution (micro-)grids are being implemented. Starting from this considerations, the superiority of dc micro-grids has been analysed also from a reliability viewpoint.

The analysis presented in the paper has also evidenced how the redundancy of the FEC in dc micro-grids is necessary, along with an adequate diagnostic system.

A. ALARMS

A detailed description of the classification of the alarms is provided in this Appendix. In the following, BOTH indicates an alarm used by both ac/dc and dc/dc converters, while AC/DC and DC/DC indicate that the specific alarm is used only by that particular converter.

A. CLASS 1

- **BOTH** room temperature close to operational limits;
- **AC/DC** main grid voltage out of bounds;
- **AC/DC** main grid frequency out of bounds;
- **DC/DC** dc grid voltage out of bounds.

B. CLASS 2

- **BOTH** overcurrent;
- **BOTH** room temperature out of bounds;
- **BOTH** power limit triggered due to out-of-bounds temperature;
- **BOTH** i-th electronic switching device's heat sink temperature close to limit;
- **BOTH** i-th magnetic component's temperature close to the limit;
- **BOTH** i-th fan's outage;
- **AC/DC** dc voltage out of bounds.

C. CLASS 3

- **BOTH** converter's outage;
- **BOTH** i-th electronic switching device's desaturation;
- **BOTH** i-th electronic switching device's heat sink temperature out of bounds;
- **BOTH** i-th magnetic component's temperature out of bounds;
- **DC/DC** storage device's voltage out of bounds;
- **DC/DC** non-uniform voltage of storage device cells.

D. CLASS 4

- **BOTH** converter's intentionally halted (local command);
- **BOTH** converter's intentionally halted (remote command).

B. MEASURED QUANTITIES

In the following the main electrical and environmental quantities that must be monitored in order to get the alarms described in Section V and Appendix A are reported. In the following, BOTH indicates an alarm used by both ac/dc and dc/dc converters, while AC/DC and DC/DC indicate that the specific alarm is used only by that particular converter.

- **BOTH** room temperature;
- **BOTH** operating hours (cumulative counter);
- **BOTH** date and time;
- **BOTH** heat sinks temperatures;
- **BOTH** magnetic components temperatures;
- **AC/DC** ac main grid voltages (phase-to-phase and phase-to-ground);
- **AC/DC** phase currents;
- **AC/DC** dc-port voltage;
- **AC/DC** dc-port current;
- **DC/DC** dc-bus voltage;
- **DC/DC** dc-bus current;
- **DC/DC** storage device voltage;
- **DC/DC** storage device cells voltages;

DC/DC storage device current.

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