Impact of a high penetration of microgeneration and µGrids in the security of supply

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ABSTRACT: The recent development of the concept of microgrid, associated to the emergent interest in microgeneration, raised a number of challenges regarding the evaluation of the technical, economical and regulatory impacts of a high penetration of this kind of solutions in the power systems. In this paper, the topic of security of supply is addressed, aiming at evaluating the influence of microgeneration and microgrids in the medium and long term availability of generation to serve the forecasted load. A Monte-Carlo based methodology is used, to compare the adequacy indices of a base case without microgeneration with the indices associated to various penetrations of different technologies of microgeneration (CHP, PV, wind, etc) and the existence of µGrids.

Keywords: Microgeneration; microgrid; security of supply; Monte-Carlo simulation.

I. INTRODUCTION

In the last decades, the interest on distributed generation has been increasing, essentially due to technical developments on generation systems that meet environmental and energy policy concerns. The interconnection of distributed generation has been predominantly confined to MV and HV levels, but the development of microgeneration technology, the decline of its costs and the public incentives to distributed generation lead to an increased installation of microgeneration (µGen) on LV networks.

Moreover, the concept of microgrid (µGrid) has been studied as a way to ease the integration of µGen in LV networks [1]-[3][5][7]. A µgrid is an association of a LV distribution network, microgenerators, loads and storage devices, having some local coordinated functions [4]-[6]. This entity can operate interconnected with the distribution network or isolated from it (using local resources).

The development of the concept of µGrid, associated to the emergent interest in microgeneration, raised a number of challenges regarding the evaluation of the technical, economical and regulatory impacts of a high penetration of this kind of solutions in the power systems.

In this paper, the topic of security of supply is addressed, aiming at evaluating the influence of microgeneration and µGrids in the medium and long term availability of generation to serve the forecasted load.

Operationally, a Monte-Carlo based methodology is used to compare the adequacy indices of a base case without microgeneration with the indices associated to various penetrations of different technologies of microgeneration (CHP, PV, wind, etc) and the existence of µGrids.

This was traditionally a HL1 (hierarchical level 1) reliability study, where the adequacy of the "centralized" generating system was evaluated using mainly probabilistic techniques. Now, with a foreseeable dramatic increase in microgeneration, some of the bulk generation will be substituted by a multiplicity of small generators, with an influence on the adequacy that must be evaluated. The establishment of µGrids as a means to ease the integration of microgeneration, along with multiple additional advantages, has also an influence on the adequacy of power availability that must be taken into consideration.

In section II, some general aspects of the generating adequacy assessment are presented. Then, in section III, the proposed methodology is presented. An illustrative example is included in section IV. The conclusion and references complete the paper.

II. GENERATING ADEQUACY ASSESSMENT

The generating adequacy of a power system has to do with the availability of generation capacity to serve the forecasted load (HL1 reliability study). Putting apart deterministic methodologies not appropriated to this kind of problem, there exist two fundamental approaches to assess the generating adequacy of a power system: analytical methods and Monte-Carlo simulation (MCS). The analytical techniques tend to be used when complex operating conditions are not considered and when the system is very reliable. On such circumstances the analytical methods are more efficient because they use mathematical solutions to evaluate the reliability indices [8]. However, the analytical techniques are unable to provide satisfactory solutions (without excessive approximations) when complex operating conditions are involved namely when there are a relatively large number of random variables. On such circumstances, the use of MCS based methods is preferable, reliability indices being estimated by simulating the random behavior of the system.

Independently of the approach, the assessment of the generating adequacy involves the development of appropriate generation and load models and the combination of these models to create a risk model containing the required adequacy indices.

Several indices may be used to evaluate the generating adequacy of a power system. The most commonly used are: the loss of load probability (LOLP); the loss of load expectation (LOLE – h/yr); the expected power not supplied (EPNS – MW/yr); and the expected energy not supplied (EENS – MWh/yr). The indices may be obtained through the use of the following expressions:

$$LOLP = \sum_{i \in S} p_i \qquad (1)$$

$$LOLE = T.\sum_{i \in S} p_i \qquad (2)$$

$$EPNS = \sum_{i \in S} C_i p_i \qquad (3)$$

$$EENS = T.\sum_{i \in S} C_i p_i \qquad (4)$$

where: p_i is the probability of system state *i*, *S* is the set of all system states associated with loss of load, *T* is the period considered (often the number of hours of an year) and C_i is the loss of load for system state i.

III. CONTRIBUTION OF µGen AND µGRID FOR GENERATING ADEQUACY

The addition of µGen capacity to a power system tends to improve their generating adequacy. Those improvements are influenced by the characteristics of the µGen technologies namely regarding their generation profiles. The profiles are influenced by natural conditions, namely: solar radiation for PV systems; wind velocity for micro-wind turbines; and temperature for micro-CHP systems. Therefore, the contribution of a µGen technology for the generating capacity tends to present seasonal and daily variations. Moreover, this contribution is influenced by the correlations between the behavior of the system load and the generation profiles of the microgenerators. In fact, a microgenerator with lower annual capacity factor may have a bigger contribution to the generation adequacy than a microgenerator with higher capacity factor, but less correlated to the load. Another issue that may influence the contribution of the µGen to the generating adequacy is the reliability of the microgenerators.

The specific contribution of a µGrid, as a whole, to the generating adequacy results from its ability to manage (or partially manage) its internal load and generation. This means that the contribution of a µGrid depends on the controllable internal µGen systems and loads. Concerning µGen, only micro-CHP systems with thermal energy storage capacity may be controlled. As a consequence of such control, those microgenerators tend to be always available to respond to capacity scarcity on the system. The contribution of a µGrid to the generating adequacy may also result from its ability to control its internal load. In fact, those entities may shed part of its internal load when a situation of scarcity of generation exists.

III. METHODOLOGY

As referred in II, the contribution of the µGen and µGrids to the generating adequacy is influenced by the seasonal and daily correlations between system load and generation profiles of microgenerators. As a consequence, the assessment of that contribution implies the use of suitable models that take into account those correlations. A possible approach to achieve this is to use a non-chronological MCS based methodology which helps accounting for the relatively large number of random variables involved (namely related to the generation profiles of µGen and its probability of failure). To capture the potential seasonal and daily correlations between variables (generation and load profiles) several scenarios may be defined. That definition should respond to two requisites: a) the number of scenarios should be as low as possible in order to avoid excessive computation times; and b) the number of scenarios should be sufficient to capture most of the dependencies between load and different generation variables. Figure 1 shows the proposed methodology, where: N the number of trials; F de number of loss of load occurrences; PNS the power not supplied due to loss of load situations.

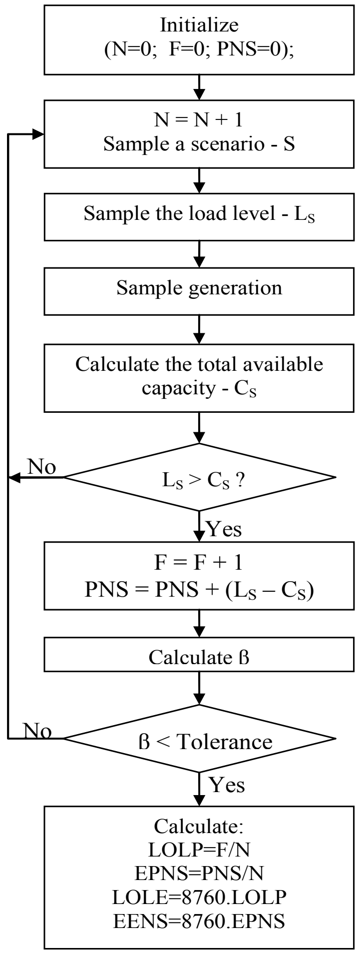

Figure 1 – Algorithm for non chronological Monte-Carlo

For each MCS trial the scenarios is sampled and, based on it, the load level and the total available generation capacity are sampled and compared in order to determine if a loss of load occurs. The simulation process is repeated until a convergence criterion is achieved. This criterion is the coefficient of variation the EENS index:

$$\beta = \frac{\dfrac{\sigma(EENS)}{\sqrt{N}}}{\dfrac{\sum_{i=1}^{N} EENS_i}{N}} \qquad (5)$$

The accomplishment of the two requisites of scenarios definition implies that each of those scenarios represents a time frame which includes some daily hours of an annual period (for instance the period between 7:30 a.m. – 9:30 a.m. of spring days). Therefore, the values of load level and generation capacity available at each scenario may vary. To account for those uncertainties, the value of the load and of the capacity factors of μGen on each scenario may be modeled through the use of suitable cumulative probability distribution functions. On such circumstances, the load level on each trial of the MCS (L_S) is sampled using the inverse transform method and the suitable cumulative distribution functions (CDF) that characterize the load behavior on the sampled scenario [8].

The available generation capacity on each MCS trial (C_S) results from the sum of the available capacity on centralized generators and the one of μGen:

$$C_S = \sum_{i=1}^{NG} F_{Gi} \times C_{Gi} + \sum_j F_{j,S} \times C_j \times CF_{j,S} \qquad (6)$$

where: NG is the number of centralized generators; C_{Gi} is the capacity of the generator i; $F_{j,S}$ is the number of microgenerators of technology j without failure on scenario S, C_j is the individual capacity of microgenerators, $CF_{j,S}$ is the capacity factor of microgenerators of technology j on scenario S; and F_{Gi} is given by:

$$F_{Gi} = \begin{cases} 0 & \text{if } U < FOR_i \\ 1 & \text{if } U \geq FOR_i \end{cases} \qquad (7)$$

where: U is a random number between 0 and 1 with uniform distribution and FOR_i is the forced outage rate of the generator i.

The value $F_{j,S}$ depends on the number of microgenerators (n) and on its forced outage rate (f) and follows a binomial distribution. For a relatively high number of microgenerators, the binomial distribution may be approximated by a normal distribution given by:

$$F_{j,S} \sim N\left(n(1-f); \sqrt{n(1-f)f}\right) \qquad (8)$$

Therefore, the number of available microgenerators on each trial of the simulation process may be obtained by:

$$F_{\mu G} = n(1-f) + \sqrt{n(1-f)f} \times U_n \qquad (9)$$

where: U_n is a normal distributed random number with mean 0 and variance 1.

The values of the capacity factor of each μGen technology on each trial of the simulation process ($CF_{j,S}$) are sampled using a similar procedure as the one defined for the load level obtaining. So, the inverse transform method and suitable cumulative distribution functions (CDF) that characterize the capacity factor of each μGen technology at each defined scenario should be used. As previously referred, those capacity factors are influenced by climacteric parameters and, as a result, tend to present seasonal and daily variations. Concerning PV generators, the behavior of the capacity factor for a specific typical day is a function of the solar irradiance:

$$CF_{PV} = \frac{I \times A \times \eta}{P_p} = \frac{\eta \times I}{\nu} \qquad (10)$$

where: P_p is the peak power of the generator; I is the incident solar irradiance (W/m^2); A the surface of the PV generator; η the efficiency of the PV system (including the interfaces); and ν the ratio between the peak power and the surface of the generator (W/m^2).

The irradiance is influenced by several factors, namely: the geographical location of the PV system; the climacteric conditions; the generator orientation and inclination with the horizontal; and the annual and daily periods. Concerning micro-CHP, the capacity factor of such units also tends to vary along the year and along the hours of the year in accordance to the thermal energy requirements. An estimative of the capacity factor for micro-CHP units along the time may be obtained using typical profiles of thermal energy consumption. The behavior of the capacity factor of micro-wind generators may be obtained through the use of wind velocity data and of a typical power curve of a micro-wind generator which may be analytically approximated as shown on figure 2.

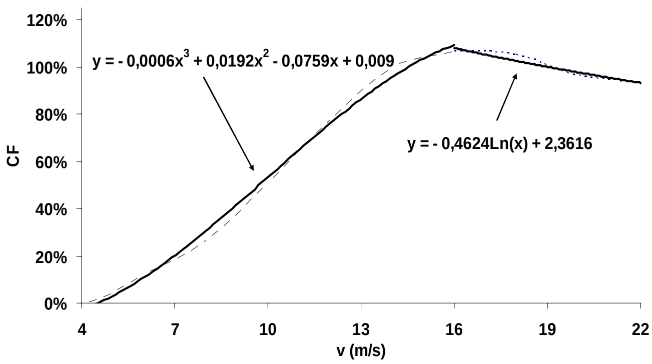

Figure 2 – Typical power curve for a micro-wind generator

IV. APPLICATION

The proposed methodology was applied to a test system adapted from the Portuguese one namely concerning load data. The conventional power system was modeled assuming a set of 400 MW thermal units with FOR = 5%.

The methodology was used to evaluate the influence of μGen and μGrids on the generation adequacy. That evaluation was made through comparison of adequacy indices of a base case without microgeneration with the indices associated to various penetrations of different technologies of microgeneration (CHP, PV, wind, etc) and the existence of μGrids. A number of possible typical situations was analyzed, namely to conclude about the sensitivity of the results to parameters like the global load level of the system, the number and dimension of microgenerators, the type of technology, etc.

A. Scenarios and CDF definition

The scenarios were defined taking into consideration the seasonal and daily behavior of the capacity factors of μGen and of the system load. An important issue here is that the capacity factors for micro-wind generators are much more stochastic than the ones of PV and micro-CHP systems. As a consequence, the scenarios to be used on MCS were defined only based on the typical generation profiles of PV and micro-CHP generators. To account for the seasonality of capacity factors of μGen and of the load, the year was divided into four annual periods corresponding to the annual seasons. Afterwards, the behavior of the capacity factors and of the system load on a typical daily of each season was considered in order to define daily periods. Figure 3 shows that information for the Portuguese situation. The PV capacity factor was defined assuming $\eta = 10\%$ and $\nu = 100\ \mathrm{W/m^2}$. The irradiance values were obtained on PVGIS Project [9] where information about average irradiance for periods of 15 minutes of a typical day of each month is available. Concerning the load, the chronological load diagram of the power system was used. The capacity factor of micro-CHP systems was defined based on reasonable assumptions.

Based on the information of figure 3, six daily periods (P1 to P6) were defined in order to take into account the daily behavior of the capacity factors and load level. So, on this case, 24 scenarios were defined, corresponding to six days and four annual periods (table 1).

Table 1 – Defined scenarios

Daily period					
07,30h - 09,30h	09,30h - 13,30h	13,30h - 17,00h	17,00h - 20,00h	20,00h - 23,00h	00:00h - 07:30h 23,00h - 24,00h
Spring - P1	Spring - P2	Spring - P3	Spring - P4	Spring - P5	Spring - P6
Summer - P1	Summer - P2	Summer - P3	Summer - P4	Summer - P5	Summer - P6
Autumn - P1	Autumn - P2	Autumn - P3	Autumn - P4	Autumn - P5	Autumn - P6
Winter - P1	Winter - P2	Winter - P3	Winter - P4	Winter - P5	Winter - P6

Subsequently to the scenarios definition, the CDF that characterizes the behavior of capacity factors of μGen and of the system load on each scenario were defined. Concerning the load, the CDF for each scenario were obtained using the chronological load diagram of the power system which contains the annual behavior of the load level for each 15 minutes period. Based on that information, histograms of the load level at each scenario were created and then approximated by typical CDF. Figure 4 shows the inverse of the CDF obtained for the period "Spring P1". Note that the approximation was made using a uniform probability distribution function (pdf).

Once the CDF are defined, the load level on each trial of the MCS is obtained by:

$$L_s = mU + b \qquad (11)$$

where: m and b are the coefficients of the line of approximation and U is a random number between 0 and 1 with a uniform distribution.

The CDF that represents the capacity factor of PV generators were obtained using data about irradiance for each of the defined scenarios. Figure 5 shows the CDF obtained for the "Spring – P1" scenario. A uniform distribution is used to approximate the obtained histogram. Consequently, the value of capacity factor for PV systems used on each trial of the MCS process was sampled using a similar procedure as the one of the load level.

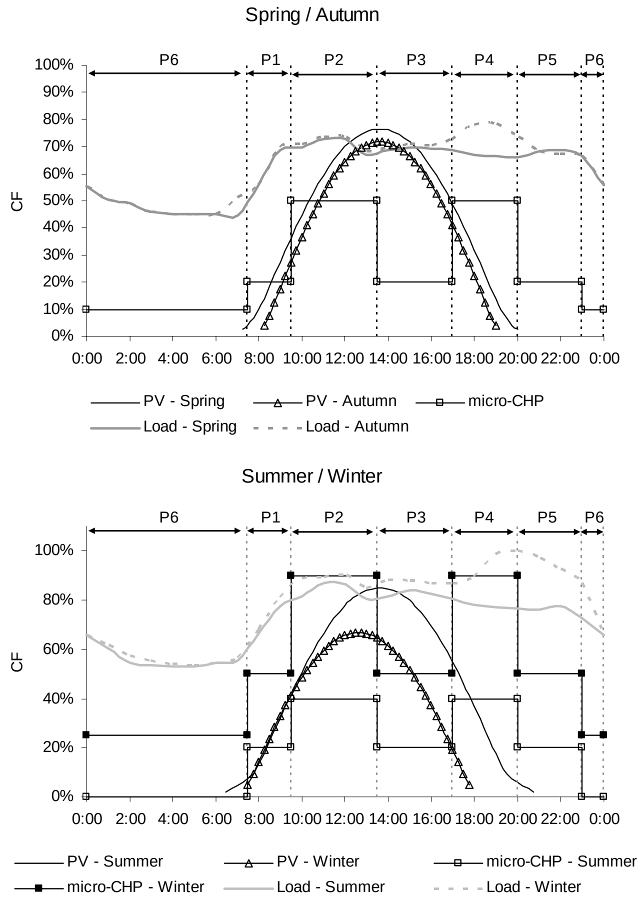

Figure 3 – Scenarios definition

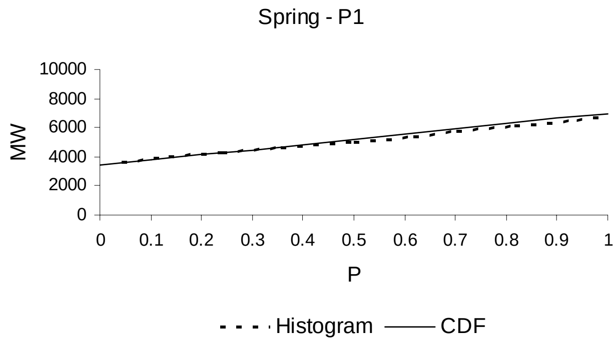

Figure 4 – CDF for load level

Regarding micro-wind systems, the CDF was obtained in a similar way as the one used to PV systems. For each scenario, histograms of the CF were calculated taking into consideration data about wind velocity and a typical power curve (figure 2). To account for the geographic variability of the wind velocity, wind data of three locations were used (Porto, Lisbon and Faro). The potential seasonal and hourly variation of wind velocity was accounted for by using annual hourly average values. Figure 6 shows, for the scenario "Spring – P1" the obtained histogram and the CDF used to approximate it. At this time an exponential distribution was used to approximate the obtained histograms. Consequently, the CF to be used at each trial of the MCS is given by:

$$CF_{Eol} = -\lambda \times \ln(U) \qquad (12)$$

where: λ is the mean of the exponential distribution corresponding to each scenario and U a random number with uniform distribution and belonging to interval [0,1].

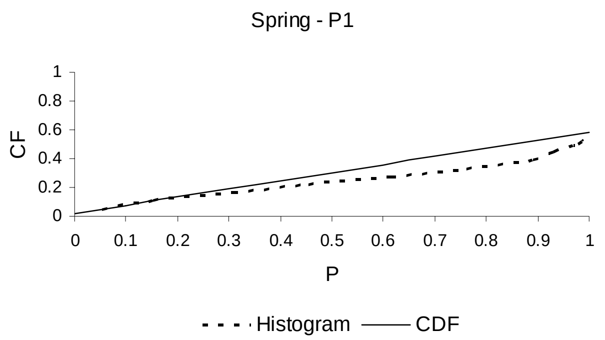

Figure 5 – CDF for PV capacity factor

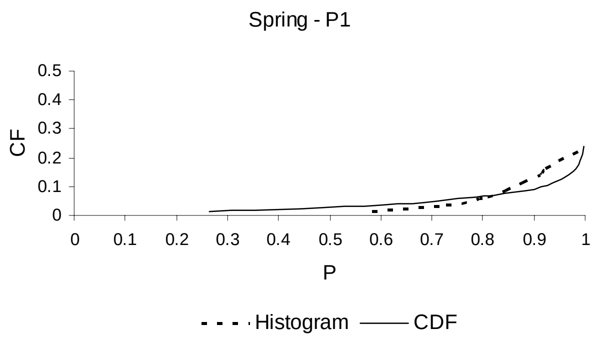

Figure 6 – CDF for micro-wind capacity factor

Concerning micro-CHP systems, its greater predictability allows the use of a typical value for capacity factor of each scenario (the values present on figure 3 were used).

B. Results

The simulations have shown that the addition of μGen to the system improves its adequacy indices. However, due to the different correlation between the generation profile of each μGen technology and the system load behavior, different improvements are achieved. This fact is shown on figure 7 for increasing penetrations of different μGen technologies on a system with initial LOLE of 27.8h.

The assessment of the influence of the μGen on the generating capacity can be done by calculating the capacity credit (CC) to the μGen. The CC is defined as the ratio between the thermal capacity that could be removed from the system without change the LOLE index and the total installed power of μGen that was added to the system.

The simulations have shown that the capacity credit to be assigned to μGen is slightly influenced by the individual capacity of the microgenerators as showed in figure 8. Figure 9 shows the influence of the probability of failure of microgenerators on the CC which is more significant than the previous one, due to individual capacity of microgenerators. Nevertheless, this influence still tends to be limited. In order to evaluate the influence of the initial reliability indices of the power system, some studies have been made assuming different values of initial LOLE (27.8 h, 2.28 h, and 0.54 h). Figure 10 shows the relevant results, which allow concluding that this influence is limited.

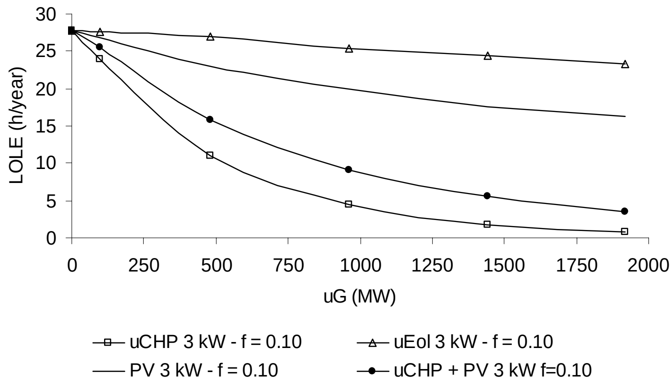

Figure 7 – Influence of μGen on the LOLE of the system

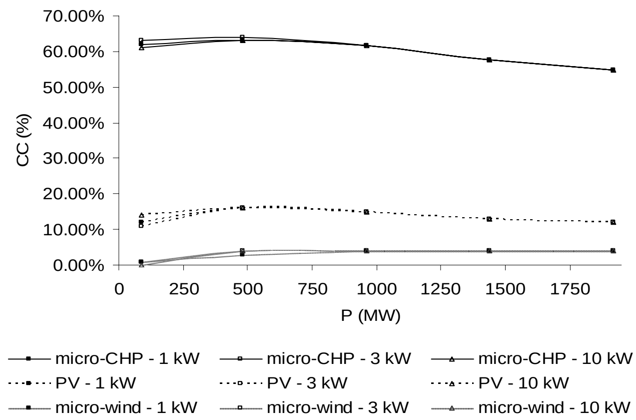

Figure 8 – Influence of the individual capacity on the CC

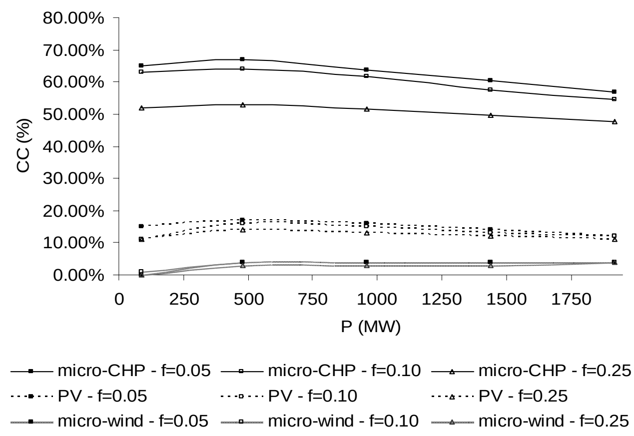

Figure 9 – Influence of FOR of μGen on the CC

The characteristics of the μGrids, namely its ability to control internal loads and generators, also makes possible to those structures to contribute for the generation adequacy. Those benefits depend on the magnitude of load and of μGen that can be actively managed by the central controller of the μGrids. Concerning μGen it is important to stress that only the micro-CHP systems may be effectively controllable once the generation of PV and micro-wind systems is imposed by the availability of the primary resources. Even for micro-CHP systems, not all of those units can be easily controlled without the waste of the thermal energy. As a consequence, only the systems with aptitude to store thermal energy should be accounted for when assessing the generation adequacy. Relating to the load management, the benefits depend on the share of the internal load that may be shed or shift from the peak period to non peak periods.

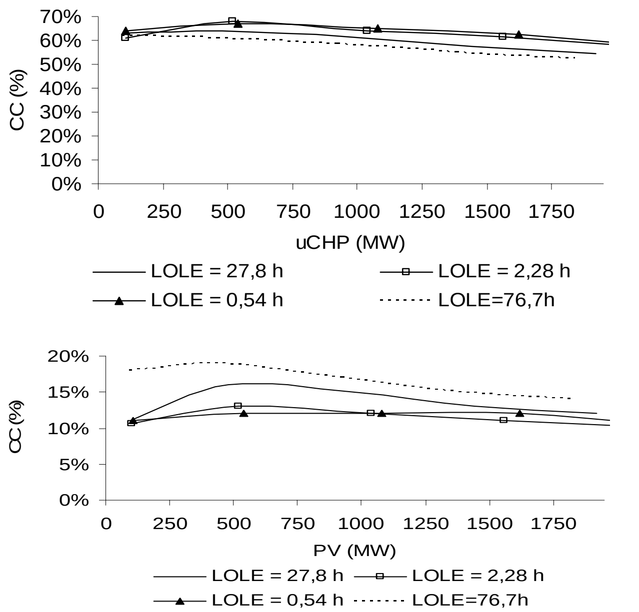

Figure 10 – Influence of initial reliability on CC

Figure 11 shows the influence of the µGrids on the CC of micro-CHP systems when different percentages of such systems are assumed as controllable (for a system with an initial LOLE of 0.54h). Concerning load control, the figure 12 shows the CC to be attributed to µGrids when assuming increasing quantities of the total system load as controllable load by µGrid's action. Note that the CC is referred to the total capacity of the conventional generation system (10800 MW).

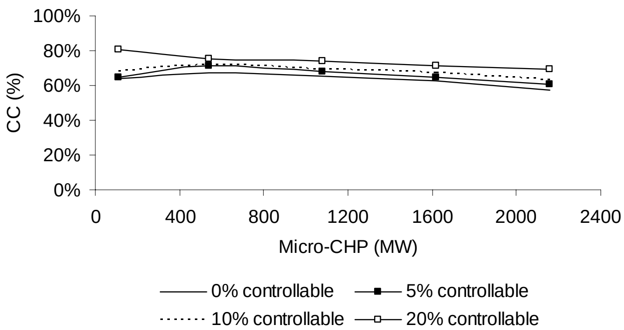

Figure 11 – Influence of µGrid on the CC of micro-CHP systems

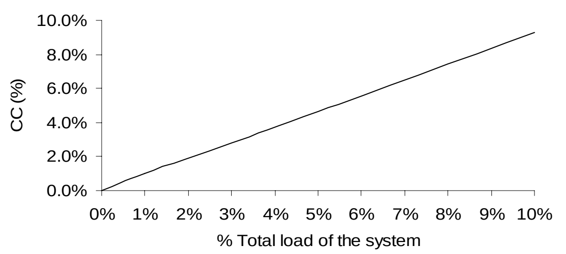

Figure 12 – Influence of µGrid on the CC of micro-CHP systems

IV. CONCLUSIONS

The paper presents a methodology, based on MCS, to compare the adequacy indices of a base case without microgeneration with the indices associated to various penetrations of different technologies of microgeneration (CHP, PV, wind, etc) and the existence of µGrids. The methodology takes into account seasonal and daily correlations between load and the generation technologies, and typical patterns of use of heat in the microCHP systems. The methodology is then used to analyze a number of possible typical situations, namely to conclude about the sensitivity of the results to parameters like the global load level of the system, the number and dimension of microgenerators, the type of technology, the initial reliability of the system, the number and dimension of µGens, the type of technology.

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VI. ACKNOWLEDGMENTS

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VII. BIOGRAPHIES

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