Fuel Cell based Distributed Generation feeding electrical and thermal loads

S. Meo, G. Paparo, G.Velotto

Abstract— **The progressive deregulamentation of the electrical energy market, together with the incentive to use zero emission energy sources, can encourage, in the middle term, the diffusion of generation sites dispersed on the territory. The utilization of cogeneration in civil and industrial installation and the technological progress associated to small and medium size systems involve increasing requests of linking to the LV and MV distribution grid, which modifies itself from "passive" to "active". Fuel Cell based electrical distributed sources, suitable to feed also thermal requirements, make the distribution utilities able to satisfy the customer requirements in terms of electrical and thermal loads, creating the opportunities to reconfigure the relation among producer, distributor and customer. The paper focuses on the performances of fuel cell sources and on their integration in the distribution networks, examining the benefits that fuel cell sources could determine on system potentialities in terms of technical and reliability aspects.**

Index Terms— **Distributed Generation; Fuel Cell Source; Electrical and thermal requirement; microring; modalities of integration; Reliability indexes.**

1. Introduction

THE recent development of the deregulated electric energy market is changing the aspect of the electrical system from a vertically integrated structure (constituted by generation plant, transmission network, passive distribution network and final customer) to a mixed structure (constituted by generation plant, transmission network, active distribution network and final customer). This is the main consequence of the new forms of installed generation plant, normally indicated as Distributed Generation (DG).

Distributed Generation (DG) includes the application of small and medium electrical generators, able to feed the electrical power required in distributed manner. Up until now, there isn't a well accepted definition of DG; however, in particular, the CIGRE' defines it as a not planning and dispatched production of electrical energy, generally connected to the distribution network and of size lower than 50 MW.

Generation plants of small-scale, with high efficiency and low environmental impact, are developing progressively. In fact, till the '80s, the power plants' sizes became more and more greater, mainly as consequence of the reduction of unit costs, fig.1. The relation between sizes and costs was already inverted at the end of the 80's, when a greater concern for environmental issues arose. Today, when a growing interest is addressed to efficient, low environmental impact and small size technologies, the applications of distributed power generation have great diffusion and more are the projects and the incentives expressly dedicated to technological development.

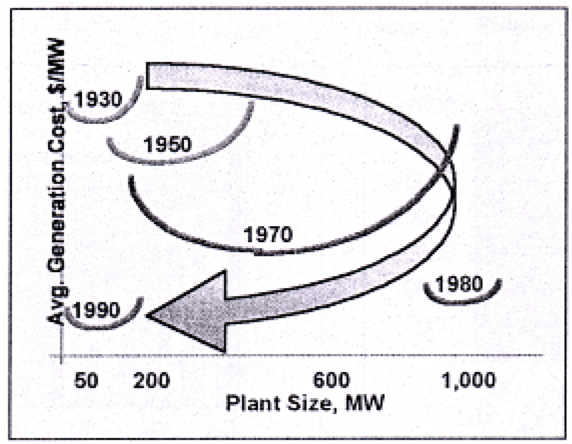

Fig.1 – Electrical Power Plant history

In the medium period, the liberalization of electrical market and the forms of incentives seem to make it possible to favor the development of zero emission electrical resources use, up until now limited by the present technological know-how, which determines high production costs. Among the these technologies, by examining the directives of the European, for instance the research projects witness FP6, it is foreseeable the development of the Fuel Cell (FC) technology and its integration in the distribution network.

A FC electrical energy source presents many notable advantages, like as: modularity, constant efficiency for varying loads, high power density, no noise during operating, reduced environment impact. In particular, the modularity favors the use of reduced size plants in network characterized by limited short circuit capability; the constant efficiency makes the plant suitable to operate also with partial load; the polluting emissions, lower than those of a conventional equivalent generating plant, make the source suitable for the diffused applications; the noise levels extremely low, due to the absence of rotating elements, make the FC source particularly suitable for dispersed residential and civil applications. Moreover, the possibility to produce electrical energy with high operating temperatures offers the bases to

The authors are with the Department of Electrical Engineering -University of Naples "Federico II" - Italy.

consider co-generation opportunity, which can result convenient in residential, industrial and tertiary installations. So, it could be desirable to study the opportunity to create diffused sites of generation, located near the final customers, and also able for micro-co-generation.

In the present context, which favors the diffusion of dispersed generations, the opportunity to create source of electrical and thermal energy must be studied with reference to both the expected load requirements and to potential energetic availabilities. In particular, these availabilities depend not only on sources' characteristics, but also on the possibility of the distribution grid to integrate the generators and make them able to operate with continuity.

It is well evident that the increasing requirements of connection to LV and MV distribution networks will impact on planning, management and control of the electrical network. In particular, among various foreseeable scenarios, there is the possibility that many electrical sources could be centered and connected in limited areas, with characteristic power requirements. In this case, it could be desirable, in reliability terms, determinate a radical change in distribution network topology, with the individuation of a series of interconnected microrings, able to feed not only electrical, but also thermal loads, fig.2. In this case it is possible to suppose that the utilities could be able to offer to the clients a series of services in order to satisfy electrical and thermal requirements. This opportunity is obviously related to evaluation of distribution network performances in a scenario characterized by multiple energy offers, among themselves various for dimension, typology and constancy.

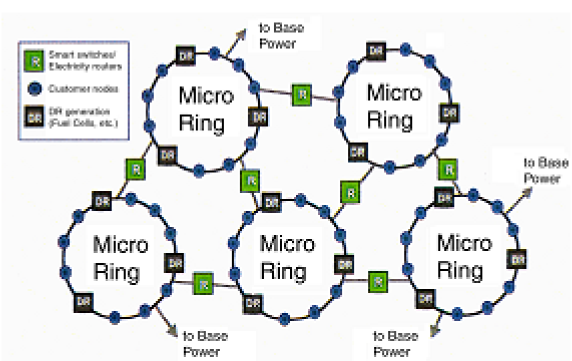

Fig.2 – Microring based -distribution network structure

The distribution network, up until now characterized by passive operation, becomes constituted by active elements, which have to be on-line managed to integrate forms of varying and decentralized generation. The connection of dispersed generation implies the individuation of a series of directives, primary related to interconnection standards and technical rules, and the assessment of performance indexes, able to determine system capabilities.

By analysing the technical problems of distribution network operating, it is evident that the DG involve main aspects as: evaluation of new stresses on electrical components, due, for instance, to higher nominal and short circuit currents; dimension of protection devices; definition of automatic control with on-line and off-line procedures; assessment of power quality; definition of procedures for system maintenance as a function of availability and reliability [1,2,3]. In particular, to assess the availability to satisfy the requirements, the evaluation of reliability indexes results a primary element for the planning of the new active distribution networks, whose reliability will result strongly influenced by the modalities of the integration of dispersed electrical sources.

On the basis of previous considerations, in the paper it is investigated on the possibility to create a distribution network with microrings, doted by FC electrical generators and able to feed electrical and thermal requirements. To evaluate the feasibility of the proposal by analyzing the potentialities of an active FC-based distribution network, there are examined both the FC characteristics, in terms of electrical and thermal performances, and the integration modalities of sources in the network, comparing various possibilities of connections in terms of reliability indexes.

2. FUEL CELL SOURCES PERFORMANCES

A. Electrical generation

FC sources as distributed generation are characterized by [4,5]:

i) high efficiency: low temperature sources (Phosphoric Acid and Polymer Electrolyte FC, PAFC and PEFC) reach 40% for a wide range of sizes and load levels; high temperature sources (Molten Carbonate and Solide Oxide FC, MCFC and SOFC) can reach higher efficiency values, about 50%. Few small and medium size conventional systems, even only in planning conditions, can achieve comparable efficiencies. However, no conventional system, unlike a fuel cell one, can reach comparable efficiencies feeding partial loads.

ii) opportunities of cogeneration: these allow a better exploitation of fuel's energy. Hybrid systems made up of a high temperature fuel cell, coupled with a gas turbine, can reach an overall efficiency higher than 60%.

iii) low environmental impact: the quasi zero emissions of CO, HC, NOx and SOx, and the considerable quietness allow the installation inside urban areas, by the delivery busbars, even where strict restrictions are effective.

iv) modular structure: this quality can allow quick expansions of systems, when increasing load requirements.

v) flexible fuel supply: Fuel cell systems doesn't give particular feeding problems because they can be fed by the existing natural gas distribution network through a reformer, which, from natural gas, is able to produce hydrogen to feed the cell.

The connection of the FC electrical source to distribution grid depends on the FC operating characteristics [6]. The FC source operates producing dc electrical power; the dc power must be converted into ac power by a Power Conditioning

Unit (PCU), fig.3, and then can be delivered to the network. The variables at the coupling busbar (bus voltage, system frequency) can monitored by a Network Interface Controller unit, which is responsible for issuing commands expressing the network requirements. The Plant Controller unit is responsible for executing the commands to ensure the integrity of the plant equipments. The presence of PCU in the system is mandatory for any ac application. On one hand, this increase the cost of the FC plant and reduce its efficiency; on the other hand, it can be seen as a adding value to the plant, providing it with electronically controlled features. The Balance of Plant device manages the status variables of reagents in input and the variables in output from the cell.

With reference to the plant response times, it is evident that the dynamic depends on the kind of FC used. In particular when the FC source feeds thermal loads, it is necessary to use high temperature cells, which present slow dynamics, like as SOFC, which are characterized by a transitory, which lasts some minutes, due to the high operating temperature. In these case the dynamics of the whole plant is normally limited by the FC and not by the mechanical components.

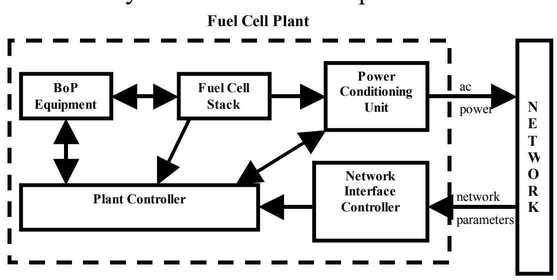

Fig. 3 – FC plant model structure

Actually, there are studying FC operation modalities addressed to:

- produce constant real and reactive powers;
- produce reactive power for voltage compensation;
- produce real power for system frequency compensation;
- produce energy with load-following mode control.

In the load-following mode the system normally can be controlled to operate in two different situations:

- residential plants using the grid only as back-up;
- islanding of plant.

In particular, in residential applications, the FC plant produces electrical power combined with cogeneration for household heating. The grid connected mode could be considered a never charged accumulator, where the power plant exports the superabundance power. Normally the FC plant provides energy to the household, and the grid furnish energy only when the electric demands reach peak values.

B. *Thermal generation*

Cogeneration is the combined production of electricity and thermal energy by a single generation plant. In a lot of applications both the energies are required; they are normally obtained with a separate production, acquiring electricity from a utility and producing thermal energy through a boiler, but it is also possible, by a cogeneration plant, to use the thermal energy of the power lost due to the production of electrical energy.

The basic scheme of a FC cogeneration plant is illustrated in fig.4 [7]. The system is composed of :

- FC stack;
- fuel processor;
- air management;
- water management;
- thermal management;
- power conditioning subsystem.

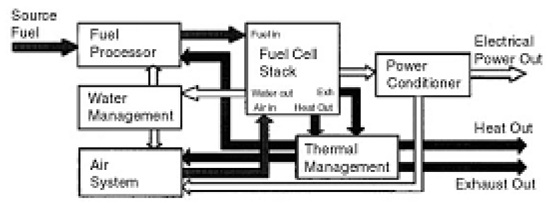

Fig. 4 – Scheme of FC cogeneration plant

Since most fuel cells use hydrogen as a fuel and most primary energy sources are hydrocarbons, a fuel processor is required to convert the source fuel (natural gas, biogas, methanol, coal gasification gas) to hydrogen rich fuel stream, cleaned according to the FC requirements; in addition to fuel, the FC requires an oxidant, which is typically air. The power conditioner and the thermal management devices are used to adequate the electrical and thermal energy to the load requirements.

In fig.5 the performances of conventional cogeneration plants and various FC cogeneration plants are compared.

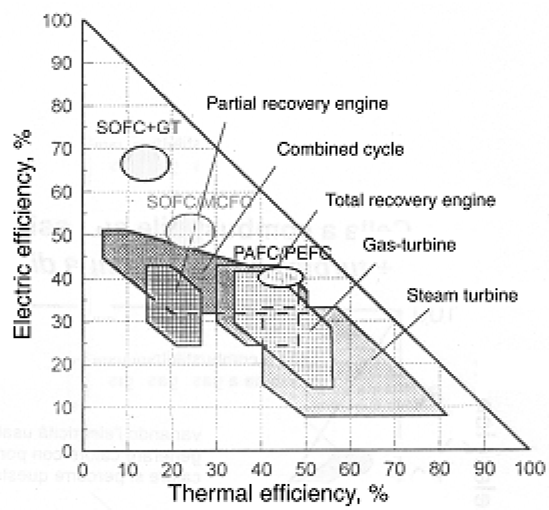

Fig. 4 – FC systems performances in comparison with traditional systems performances

An overlap exists only between the PAFC and PEFC cogeneration systems and the internal combustion engines or gas-turbines (GT). Particularly considering the rating of PAFC and PEFC plants (some hundreds of kW) the comparison is with micro gas-turbines that are raising on the market in these years. The MCFC and SOFC cogeneration systems and the hybrid SOFC/GT systems have better performances than those of conventional plants. It is evident that the conventional cogeneration technologies are not able to reach such performances and, among the conventional technologies, only the combined cycle plants of hundreds of MW reach the characteristics of FC plants.

By the diagram it is clear that the FC cogeneration plant have great efficiency compared with the conventional technologies, and, moreover, in a number of other areas, FC systems promise to exhibit performance comparable to existing systems: response time; useful life; maintainability; cost.

FC which are already operating at their design temperature typically respond quickly to load changes. Often the rate of response is more a function of the auxiliary systems such as the air compressor, fuel processor, etc., than the FC stack itself. For high temperature fuel cells such as the MCFC and the SOFC, the time to reach operating temperature can be significant and these systems tend to be more appropriate for generating power for large-scale applications that operate either continuously or for long periods of time.

3. Grid Reliability Performances

On the basis of the economic convenience, expressed in terms of the ratio utility offers and customer requirements, the opportunity to configure the topology of the distribution grid with rings doted by dispersed FC sources depends on the potentiality obtainable in terms of reliability indexes.

The integration of distributed sources in the distribution network could determine the change in the structure and operating modality of the electrical system. Normally, the distribution network's topology, which is the effect of a long planning work, is the synthesis of objectives related to: simplification, reliability, costs, and environmental impact. The choice of structure and operating modalities is made in order to: balance the load flow, ensure an acceptable availability level, limit transmission and distribution losses, ensure a satisfactory voltage profile. The integration of sources directly acts on the network reliability as a function not only of the size, distribution and performances, but also of the connection modalities of the sources integrated in the specific topology.

In order to assess grid reliability, various indexes can be evaluated; among these, the Annual Energy Not Supplied (ENS), due to faults or unavailability, is frequently adopted. The index is a function of the components' reliability, system topology and, eventually, possible reconfigurations.

The topologies normally adopted can be organized as: radial, loop and double sources structures. In particular, favoring the protection device operations by acting on the central breaker, it is frequently to recognize a radial operating modality even in structures doted by double sources, fig.6. At the right and left sides there are two primary stations, which are able to feed the loads (in figure indicated as 1..N), each one normally connected to the feeder by two controlled breakers; the breakers operate to isolate the fault and make it possible to feed the loads through the right and the left sides. The central breaker is normally opened and the two sources feed the respective loads separately; when the contingency occurs, opening the breakers near the fault, it is possible to isolate it and the sources are newly able to feed the loads with a new configuration.

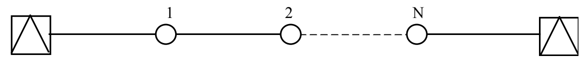

Fig. 6 – Double sources structure

In this case, assuming:

g_A mean number of annual faults at each delivery busbar,

d_A mean time to repair of a delivery busbar (MTTR),

p_A the probability of source's unavailability ($p_A=g_A*d_A$),

p the probability of line's unavailability,

N the number of electrical stations (representing the loads),

E the annual energy output of each electrical station, the ENS could be expressed as [8]:

$$ENS = N\,E\,p_A^2 + 2N\frac{N+1}{2}E\,p\,p_A + \frac{(N+1)(N+2)}{6}N\,E\,p^2 \qquad (1)$$

In the case of loop topology, there is only one source and the loads can be fed through two different sides, as in the previous scheme. The topology, fig.7, can be considered a particular kind of double source structure fed by both terminals by the same primary electrical station.

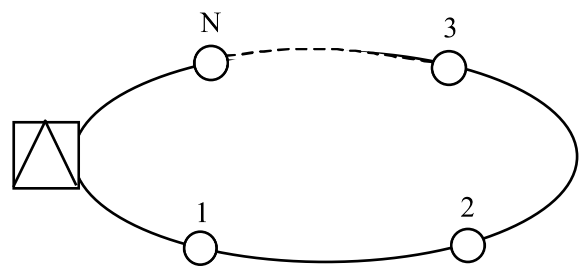

Fig. 7 – Loop structure

In this case, it is possible to express the ENS index as:

$$ENS = N\,E\,p_A + \frac{(N+1)(N+2)}{6}N\,E\,p^2 \qquad (2)$$

which result less the previous, as consequence of availability of only one source: in this case the ENS index is strongly influenced by the probability of source's unavailability. The reliability of a loop is comparable with the double source if the electrical station has a backup source.

Considering the DG centred in limited areas and assuming the opportune values for the variables, it is possible to use the eq.(2) to evaluate the reliability function which is of a single loop in a microring based distribution network. Moreover, in this case, it is necessary to assess the incidence of the integration of an alternative FC source on the ring reliability function.

The reliability function depends on the source connection arrangement. Mutual from the experience of the transmission grid, it is possible to define two different solutions, which foresee, with different reliability functions, double breakers and feeders, fig.8, or one breaker and one feeder, directly connected in stationary, fig.9.

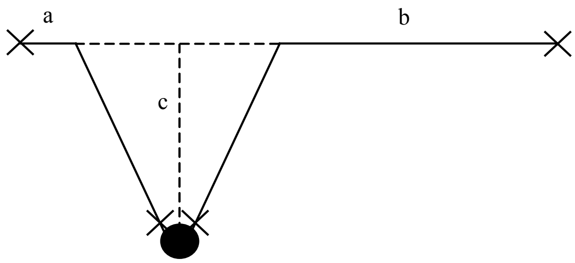

Fig.8 – Integration of DG source with double feeders

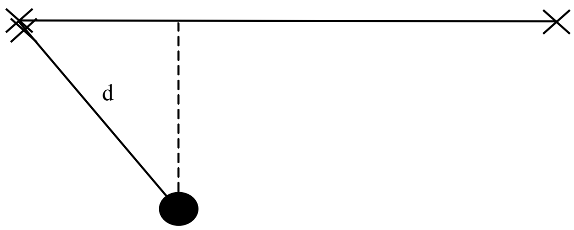

Fig.9 – Integration of DG source with only one feeder

The first is more reliable and expensive, whereas the second permits to reduce the number of components, resulting acceptable where there is not necessary to ensure high reliability value.

A comparison between the two different structures can be made on the basis of the assessed unavailability, considering both the accidental faults and the planned maintenance periods. In this case, assuming that contemporaneous faults or maintenance operations do not occur, the unavailability index for the first scheme is equal to zero, because of there is always possibility of connection to the grid, whereas for the second it results a function of the mean number of faults and time to repear, tab.I.

TAB.I
Unavailability index for DG source integration

Case	*Accidental fault duration*	*Maintenance duration*
double	0	0
Single	g_a*d*D_a	f_p*T_p*d

where:

g_a is the mean frequency of accidental fault [number of faults/year];

D_a is the mean time to repair [h/km];

f_p is the mean frequency of planned maintenance[number of maintenance/year];

T_p is the mean maintenance time per kilometer [h/km].

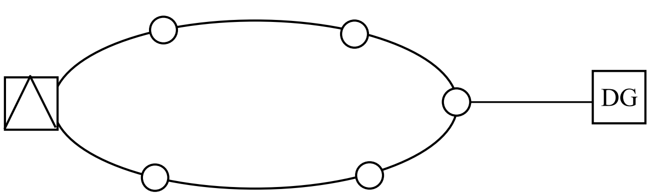

Fig.10 – Integration of DG source in a loop structure through one feeder

Defined the reliability function of the DG source connected to the ring, it is possible to evaluate the increase of system reliability due to sources integration. In particular, assuming to use the scheme of fig.9, to evaluate the new reliability of a ring, as a function of the connection of a new distributed source, fig.10, it is possible evaluate the following general equation, assuming that the DG is able to feed all loads present in the loop structure and that the electrical substations are equally distributed in the two half-loop structure:

$$\mathrm{ENS}=\sum_{i=1}^{N}\left\{1-\left\{\begin{array}{l}(1-p)^{\frac{N+1}{2}}\left[1-p_A p_G\right]\left[(1-p)^{i}+(1-p)^{\frac{N+1}{2}-i}-(1-p)^{\frac{N+1}{2}}\right]+\\ +\left[1-(1-p)^{\frac{N+1}{2}}\right]\cdot\\ \cdot\left[(1-p_G)(1-p)^{\frac{N+1}{2}-i}+(1-p_{\mathrm{A}})(1-p)^{i}-(1-p_{\mathrm{A}})(1-p_G)(1-p)^{\frac{N+1}{2}}\right]\end{array}\right\}\right\}\mathrm{E} \quad (3)$$

where p_G is the probability of DG's unavailability, including also the feeder's unavailability.

This equation, compared to eq.(2), permits to define the incidence of integration of the source. On the basis of values of variables and on load requirements, it is finally possible to determine the opportunity of integration.

4. Conclusions

The convenience to install small, low emission electrical sources, able also to satisfy thermal loads, make it possible to determine the basis to create the diffusion of many electrical sources, forcing the utilities to interconnect themselves to the grid. Even if the utilities are interested in the access of new producers to the power electric grid, they are reluctant to modify the present state of the grid, due to the large investments. The availability of distributed small sources in restricted areas could create the opportunity to realize distribution microrings, whose potentialities, in terms of electrical and reliability aspects, it is desirable to be assessed. On the basis of the evidence that in the electrical energy market the competitiveness is ensured only with distribution grids able to interconnected all the sources, possibly without any technical or operational constraints, the opportunity to reconfigure the network can result an useful tool to adequate the electrical system to the forcing requirements.

It is evident that the transformation process will require new rules and interconnection directives for the DG, which need to be accurately assessed and defined, in agreement with the principles of the new deregulated market.

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