OPTIMAL CHP OPERATION IN MICROGRIDS TO DEFER NETWORK ASSETS' UPGRADE

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ABSTRACT

The paper aims at assessing the economic benefits achievable by a district of industrial and commercial customers aggregated in a MicroGrid (MG) with several CHP fuel cell power plants; CHP is an ideal application for the fuel cell. In the MG, generators and responsive loads are controlled with a central controller (MicroGrid Central Controller, MGCC) that establishes the set-points of the local controllers in the power electronic interfaces, in order to minimize the management cost. The MGCC receives market signals, load and generation bids, and determines the correct dispatch of generators to maximize the value of the MG by optimizing its operation and minimizing the energy bills paid to purchase electric power and produce heat/cooling.

INTRODUCTION

Active distribution networks are widely regarded as solutions able to facilitate the integration of Distributed Generation (DG), maximise customer participation, postpone network investments, and increase the energy efficiency. The connection and management of DG in the distribution network is the first challenge facing Distribution System Operators (DSOs) in making the transition towards active, integrated networks. One of the possible evolutions of the future MV distribution system is represented by the MicroGrid (MG), which consists of a combination of generation sources, loads and energy storage operated as a unique controlled electrical unit [1].
From the system operator's point of view, an MG can be regarded as a controlled entity within the power system that can be operated as a single aggregated load and, given attractive remuneration, as a small source of power or ancillary services supporting the network. From customer's point of view, MGs provide thermal and electricity needs, but also enhance local reliability, reduce pollution, improve and, potentially, decrease the costs of energy supply.
There is the need to introduce innovative power conversion systems, suitable for the scenarios that include new power production technologies, as Fuel Cells (FCs).
The paper aims at assessing the economic benefits achievable by a district of industrial and commercial customers in MG with several FC power plants, interfaced by inverters.
In the MG, the generators and responsive loads are controlled with a central controller (Microgrid Central Controller, MGCC) that establishes the set-points of the local controllers. The central controller receives market signals, load and generation bids, and determines the correct dispatch of generators to maximize the value of the MG by optimizing its operation and minimizing the energy bills to purchase electric power and produce heat/cooling.
In the paper the network simulation tool permits quantifying the DG side effects, by considering the distribution network characteristics (lines and network configuration). The simulation studies with innovative high efficient FC technologies (PEM, suitable for thermal loads that do not require steam) have highlighted the important benefits of the combined energy/heat production, related to the reduction of fossil fuel usage.
The proposed tool may be used to assess the economic benefits of MG, FC CHP equipped, with reference to the innovative management of existing assets. The savings earned by the customers connected to the MG are also evaluated (e.g. better exploitation of fuel with CHP).

MICROGRID CENTRAL CONTROLLER

The MGCC acts as an aggregator of loads and DG with different technologies that determines the optimal power dispatch with the final goal of minimizing the global energy bill. Considering the MG as a unique entity, the MG costs to be included in the economic evaluations are the costs of DG power generation, the cost of the energy purchased by the MG to supply the loads, and, finally, the total revenues from the energy selling to the grid. The MGCC coordinates the local controllers of both DG and responsive loads and guarantees the load being supplied with a prefixed level of reliability.
More in detail, the key functions of the MGCC are [2]:

- to provide the individual power and voltage set point for each DG controller;
- to guarantee that heat and electrical loads are met;
- to minimize emissions and system losses.

The MGCC optimisation is based on several input data: DG power bids, energy market prices, technical limits of the DG, DG generation costs, demand forecasts, heat demand, and scheduled interruptions for maintenance. The Distributed Energy Resources (DER) follow the centralized commands given by the MGCC that provides only basic dispatch commands to operate all together, and to assure, under a range of operating conditions, a high quality of service to the MG loads with economic benefits. The local controllers modify power production and load demand, and prepare bids for the next time interval on the basis of the set points elaborated by the MGCC.
In previous papers, the authors developed a NN-MGCC

(Neural Network MGCC) [2], for the MG optimal management, and a Distribution Management System (DMS) [3] to solve some contingencies in active distribution networks (voltage regulation problems, line overloads, etc.). In the paper, the Objective Function (OF) of the DMS in [3] has been improved in order to use the implemented algorithm for MG application. In the next section is presented the new OF adopted.

The objective function

The optimization algorithm has to find the optimal combination of the operation options to minimize operation costs without causing violations of the constraints. The OF (1) takes into consideration the energy losses, the cost of power production, the cost of load shedding and the cost/revenue from energy to power grid.

$$\min \sum_{i=1}^{N_{branches}} \delta_i \left|F_i\right| + \sum_{j=1}^{N_{DG}} c_{DG}^{j} P_j + \sum_{k=1}^{N_{DSR}} \gamma_k P_k^{DSR} + p\ F_{grid} \qquad (1)$$

With some approximation, the OF can be expressed as a linear combinations of line flows, curtailed power, and shed power [4]. In the paper, the optimization algorithm also takes into consideration nodal voltage violations and the effect of reactive power injections.

The first summation in (1) is proportional to the cost of the energy losses. F_i is the active power flow through the i^{th} branch of the network. δ_I is a coefficient that allows estimating the cost of energy losses. Eq. (2) gives the approximated value of the cost of energy losses in the network, C_{loss}.

$$C_{loss} = \sum_{i=1}^{N_{branches}} \left(\frac{c_l \cdot \Delta t \cdot r_i \cdot F_{avg}}{3 \cdot V_n^2} \right) \cdot \left|F_i\right| = \sum_{i=1}^{N_{branches}} \delta_i \left|F_i\right| \qquad (2)$$

c_l is the unitary cost of the energy lost, V_n is the nominal voltage, r_i is the resistance of the i branch, Δt is the time interval between two successive real-time calculations. The average value of the estimated power, F_{avg}, equal for each network branch in order to not penalise specific paths in the optimisation process, is used to obtain an estimate of the average losses.

The second summation in (1) takes into account the active power dispatch to reduce energy losses and minimizing the MG energy bill. In (1), c_{DG}^{j} is the cost for producing one kWh with the j^{th} DG unit, N_{DG} is the number of the generators connected to the MG, P_j is the real power output of the j^{th} DG unit.

The third summation in (1) represents the cost for shedding the responsive loads (DSR) in the network. P_k^{DSR} is the power shed from the k^{th} load, N_{DSR} is the number of the DSR loads, γ_k is proportional to the cost of power shedding.

Finally, the last summation takes into account the market cost of energy or the profit earned by selling energy to the grid; p is the hourly market energy price, whereas F_{grid} is the active power flow through the interface point between the MG and the bulk (public grid).

In order to linearize the optimization problem, the power flow F_i is expressed by means of two non-negative quantities, X_i and Y_i, which cannot be both nonzero at the same time. The optimization problem can be stated as follows:

TABLE I - GENERATOR DATA

CAPEX CHP [€/kW]	CAPEX no CHP [€/kW]	O&M [€/kWh]	Primary source
3000	2500	0.120	Methane

$$\min \sum_{i=1}^{N_{branches}} \delta_i (X_i + Y_i) + \sum_{j=1}^{N_{DG}} c_{DG}^{j} P_j + p\ (X_{grid} + Y_{grid}) \qquad (3)$$

subject to:

$$\begin{bmatrix} A & -A & 0 & 0 & B_g & B_{DSR} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & tg\varphi & A & -A & 0 & B_g \\ 0 & 0 & 0 & \frac{dv}{dP} & 0 & 0 & 0 & 0 & \frac{dv}{dQ} \\ 1 & -1 & 1 & 0 & 0 & m^B & -m^B & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & m^g & 1 \end{bmatrix} \begin{bmatrix} X_P \\ Y_P \\ S_P \\ P \\ P^{DSR} \\ X_Q \\ Y_Q \\ S_Q \\ Q \\ S^{PW} \end{bmatrix} = \begin{bmatrix} P_{node} \\ Q_{node} \\ \Delta V \\ q^B \\ q^g \end{bmatrix}$$

$$\left[X_P\right], \left[Y_P\right], \left[S_P\right], \left[X_Q\right], \left[Y_Q\right], \left[S_Q\right], \left[S^{PW}\right] \geq 0$$

where [A] is the node to branch incidence matrix, $[B_g]$ and $[B_{DSR}]$ are binary matrixes introduced to insert DSR and DG unit into power flow equations, $tg\varphi$ is referred to DSR loads (the DSR loads are considered with a constant power factor), $[S_P]$ and $[S_Q]$ are the vectors of slack variables (for active and reactive flow, respectively) containing the residual power for each branches, P^{DSR} is the vector of the shedding powers, P is the vector of the generated powers, P_{node} and Q_{node} are the nodal powers.

The DG can help regulate voltage by injecting reactive power. For this reason, the optimization problem is subject to voltage constraints that are expressed according to (5).

$$\Delta V = \sum_{k=1}^{nbus\_GD} \left(\left.\frac{dv}{dP}\right|_k \Delta P_k + \left.\frac{dv}{dQ}\right|_k \Delta Q_k \right) \qquad (5)$$

where ΔV is the sum of the voltage deviations with reference to the nominal voltage, $\left.\frac{dv}{dP}\right|_k$ and $\left.\frac{dv}{dQ}\right|_k$ are the sensitivity indexes calculated according to [5].

Finally, the k^{th} generator have to comply with the power capability curve, that limits the active and reactive power production. The capability curve is approximated with a piecewise linear to maintain the linear formulation. Assuming that N_{seg} is the number of straight lines used to approximate the generator capability curve, for each generator N_{seg} the considered inequality constraints are in (6).

$$P_k + m_{jk}^{g} Q_k + S_{jk}^{PW} = q_{jk}^{g} \quad j = 1 \ldots N_{seg}, \quad k = 1 \ldots N^{DG} \qquad (6)$$

m_{jk} and q_{jk} are the slope and the intercept of the j^{th} line used to approximate the capability curve of the k^{th}

generator; S_{jk}^{PW} is a non-negative slack variable to transform the inequality constraint into an equality one.
A similar approach is also used to take into account the transport capability of lines.

CASE STUDY

The proposed MGCC has been tested by simulating the behaviour of industrial and commercial loads sited in area destined to industrial/commercial activities. The test MG supplies 5 nodes and it is operated as an open loop. The lay-out of the MG is represented in Figure 1. The peak of the electrical demand is equal to 420 kW. To reduce the cost of services paid by customers in the area, it has been hypothesized to resort to DG (FC).
Table I shows the data assumed for the FC generator: the capital expenditures (CAPEX, with and without CHP), and the Operation and Maintenance costs (*O&M*). The cost of DG power generation for the generic *i-th* generator, C_{DGi}, depends on the dispatched power P_i according with (7).

$$C_{DG_i}\left(P_i\right) = O\,\&\,M \cdot P_i \tag{7}$$

The hourly power production (*E*) is related to the hourly heat demand (*H*) by means of (8).

$$H = \alpha \cdot E \tag{8}$$

where α is the inversed of the electrical index (net electricity divided by the useful heat, assumed equal to 1.00 in this application).
Electrical and thermal loads are modelled with variable impedances according to their typical daily curves. There are no limits on the number of load curves that can be considered.

ECONOMIC ANALYSIS

A facility owner, among the investments that produce cost savings or favourable life cycle costs, needs to be driven by the investment that will be paid back most quickly. Thus, this section is devoted to compare from an economic point of view several scenarios constituted by different assets of FC units. For the sake of simplicity, the economic analysis is based on equity investments, disregarding taxes. Such simplification is reasonable

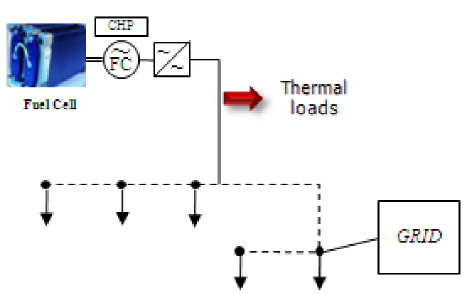

Fig. 1. The MG used to assess the MGCC performances.

whether it is observed that in the area of the MG, which is already destined to industrial facilities probably there are no more municipal taxes to pay for land use.
The economic evaluation criteria adopted to assess the profitability of the investment are the *Net Present Value* (*NPV*) and the *Discounted Payback Time* (*DPT*).
The *NPV* is equal to the present value of the future cash flows return by a project, minus the initial investment; it gives a measure of the expected addition to the investment wealth and it is useful to choose the worthwhile investment between different alternatives. The *NPV* can be expressed as in (9).

$$NPV = \sum_{t=1}^{N} \frac{ACF_t}{\left(1+k\right)^t} - IO \tag{9}$$

Where ACF_t is the annual cash flow in year t, k is the appropriate discount rate, also known as the capital cost, *IO* is the initial outlay of cash (investment amount, Tab. I) and *N* is the project's expected life. This equation discounts each year's cash flow back to the present, then deducts the initial investment, which gives a net value of the investment in today euros. In general, when evaluating different investment alternatives, a positive *NPV* during the service lifetime indicates that the investment has a positive effectiveness.
The *DPT* measure indicates the number of years required to recover the initial investment, and represents an alternative means of evaluating the cost–benefit of a project. It is well known that a more effective investment is represented by a smaller DPT value.

RESULTS AND DISCUSSION

Several simulation cases have been performed to evaluate the economical feasibility of the MG under test. The cases differ for the DG penetration level (PL) in terms of the number of FC units (the different cases are obtained using one or more than one 10 kW FC), and for the adopted operation mode, as reported in Tab. II. In the last column of Tab. II, the percentage of thermal load covered by CHP, in terms of nominal power is reported. Starting from the first case, where no MG operation is implemented and loads act in the market to purchase energy, all the other cases are managed by the proposed MGCC. The CHP operation of the FC implies the MGCC cannot completely dispatch it because the heat demand has the priority (cases 2-5 in Tab II). Finally, the case 6 of Tab. II evaluates the MG feasibility without CHP. No responsive loads are considered in the simulations.

Case 1: no DG installed in the area

In this case, no DG is installed in the area. The loads are not coordinated and the MG purchases electrical energy at market prices. The thermal loads are satisfied by conventional boilers. In this case the global annual energy bill is equal to 372 k€ and can be calculated considering the cost of the electrical energy (311 k€) and the cost of fuel for heat demand (61 k€).

TABLE II – DG PENETRATION LEVEL AND CAPACITY

	PL [%]	P_n [kW]	%CHP
Case 1 (no MG)	0.0%	--	--
Case 2	2.4%	10	10
Case 3	11.9%	50	50
Case 4	23.8%	100	100
Case 5	100.0%	420	420
Case 6	23.8%	10	0

Cases 2, 3, 4 and 5

The DG penetration levels considered are showed in Tab. II. In order to evaluate a condition of power production surplus respect to load and thermal demands, the case 5 with a high value of *PL* (100%) has been considered. Tab. III shows the economic results. In all cases, the global energy bill is obtained by summing the production cost for DG unit (dispatched by the MGCC) and the cost of the energy purchased from the bulk power in those hours where the internal production cannot satisfy the load demand due to technical or economical reasons. Obviously, the global energy bill can be reduced with the revenues achieved by selling energy in some profitable hours. In Tab. III, for each case, the values of the indicators adopted for the economic evaluation of MG are reported. The CAPEX (*IO*, in Tab. III)), corresponding to the DG penetration level of Tab. II are calculated with the data of Tab. I. It is assumed a cumulative saving during 15 years, based on the estimated life of the system, and an increasing of the cost saving value by 5% a year (conservative). The profits in Tab. III are calculated as the difference between the annual energy bill respect to case 1. In other words, profits represent the possible savings that can be earned by changing from the traditional to the MG operation. The last column of the table III shows a measure of the cost/benefit ratio. The simulations highlight the important benefits of the CHP, related to the reduction of fossil fuel usage, which is equal to 90% about in all cases.

Case 6

In case 6, the DG penetration level is the same of case 4, but the FC units adopted are not enable to cogeneration. As it is easy to see, despite the reduction of initial investment respect to case 4, the inapplicability of the CHP reduces consistently the profit (only 0.3%) and the investment is not profitable.

Discussion

Analyzing the results, it is important to remark that the implementation of the MG with CHP FC units, equipped with a MGCC allows achieving significant saves with the active participation in the energy market, selling and buying energy from the bulk power, and reliably satisfying the electrical and thermal demand. The initial investment obviously increase with the number of DG unit, but in the proposed cases also the profit increases with the DG unit number. This is because it depends on the difference between the installed capacity and the electrical loads: the bigger this difference, the greater the energy availability for the sale in the peak hours. The comparison among all the cases demonstrates that the first two investments proposed are profitable. In the no CHP operation mode (case 6), the investment is not profitable, because the cost of oil to be burnt for heat demand is very high.

TABLE III - ECONOMIC RESULTS FOR DIFFERENT FC CONFIGURATIONS

	PL [%]	*IO* [k€]	*Profit* [%]	*DPT* [years]	*NPV* [k€]	*NPV/IO*
Case 2	2.4%	30	2.2%	3.90	100	3.3
Case 3	11.9%	50	9.4%	4.50	400	2.7
Case 4	23.8%	300	14.5%	5.80	500	1.7
Case 5	100.0%	1260	15.9%	--	--	--
Case 6	23.8%	250	0.3%	--	--	--

CONCLUSIONS

In this paper an economic evaluation of a MG with a FC unit has been presented, applied on a real case study. The results show that a MG can be convenient with an optimal management system (MGCC), derived by a DMS application. The economic benefits are significant. CAPEX may be fully paid back within a reasonable time, in particular condition. It is important to observing that in order to maximise the MG value it is not only necessary to define the size of DG, but also the number, the position and the type of generators [6]. Despite the high installation cost of FC, when used in CHP operation mode, are clean and efficient energy supply, especially when compared to other fossil fuel energy production methods. In conclusion, MGs have great economical potential for favouring the integration of FC, especially if, in the future, the installation cost will decrease.

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