Emission reduction and economical optimization of an urban microgrid operation, including dispatched PV-based active generators

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***Abstract*—In order to take full advantage of distributed generators, an evolution of the classical power system organization and dispatching is also necessary. An aggregator of a residential urban electrical network is considered by the Distribution System Operator as a stakeholder, which is able to control a cluster of local generators and loads with technical constraints for the connection with the remaining distribution grid and commercial contracts with outer electrical producers. This paper is focused on the design of the Microgrid Central Energy Management System which relies on a 24 day ahead operational planning and an adjustment procedure during the operation. A dynamic programming-based algorithm is derived to solve the Unit Commitment Problem with a multiobjective function in order to reduce the economic cost and CO2 equivalent emissions. The energy management system is implemented and tested by using a hardware-in-the-loop simulation of the urban network. Economic and environmental gains are evaluated.**

***Index Terms*—Distributed generators, energy efficiency, energy management system, microgrid, optimization, operational planning, smart grid, storage, renewable energy**

I. INTRODUCTION

Research activities are more and more headed towards solutions for satisfying the ever growing energy demand.

In order to ensure our continuous development in a sustainable way, a considerable portion of the electrical energy has to be generated by Renewable Energy Based Generators (REBG). One of their main drawbacks is the non-constant nature of the primary energy source (solar irradiation, wind, …). Hence, the increasing of the REBG penetration into the energy mix could cause difficulties for system operators in matching the power production and demand thus degrading the quality of power supplied to the customers and further causing disruptions in power supply [1]. Moreover further investments have to be made in conventional generators to create additional power reserve for compensating the cyclic and stochastic nature of renewable energy.

Alternative to grid reinforcement could be a restructuring of the power system architecture and an increase of the share of Distributed Energy Resources (DER) that generate electricity at a local scale. Hence micro gaz turbine based CHP and PV generators play an essential role for domestic small scale electricity generation (fig.1).

Fig. 1. Micro CHP and 17kW PV panels at L2EP laboratory

A first restructuring strategy is to abandon feed-in tariffs and favor self-consumption of home produced electricity through incentives as experimented in Germany [2]. But this energy policy restricts the energy sharing for neighborhood customers and limits the energy security and the prevention of over-invest in production plants prevents by effect of expansion.

A further strategy is to transform actual PV generators into controllable Active Generators (AG) in order to offer new flexibilities for energy management of electrical networks. In this paper, considered active PV generators contain batteries for long term energy reserve availability and ultra-capacitors for the power supply with very high dynamics. Thanks to these embedded storage technologies and the dedicated local control algorithm, this generator is able to deliver prescribed power references, power system services and can be dispatched to the distribution system operator (fig. 2).

But the current electrical transmission and distribution networks are rather passive and centralized from the supervision point of view, which makes it difficult to coordinate the operation of DER in the grid, as they are not dispatched [2]. The Smart Grid (SG) organization has to incorporate distributed intelligence and interactive communication at all levels of the electric network in order to improve efficiency, reliability, security and coordinate power generation in an optimal way [3], [4]. With the integration of REBG in areas with low local consumption, the power flow

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may temporally reverse the power direction. Anyway, the availability of information from sensors enables the design of a dedicated local energy management system in order to implement two-way flows of electric energy and to create an automated distributed advanced energy distribution network.

A step towards the SG is to integrate locally REBG, conventional generators and loads in clusters called microgrids. These microgrids may be operated in islanded or connected mode (with the distribution grid) and also provide ancillary services to the grid [5-7]. They must be locally aggregated and controlled by a Microgrid Central Energy Management System (MCEMS) (Fig. 2) and are considered by the Distribution System Operator (DSO) as a stakeholder, which is able to locally control a cluster of generators and flexible loads

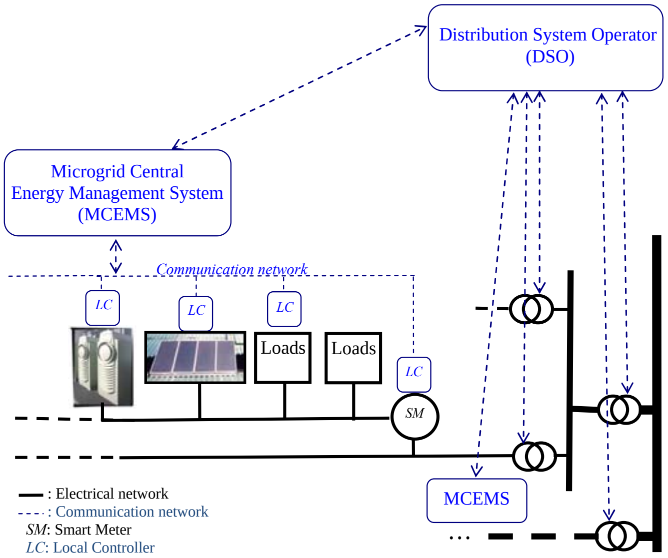

Fig.2. A Smart Grid based on the concept of microgrid integration

The main problem to overcome is to match locally the power demand and the production in an optimal way while minimizing the use of non-renewable energy sources for electricity generation and decreasing economic costs [8-9]. The contributions of this paper are practical methods and solutions to design two stages of the MCEMS taking into account environmental and economic tasks.

A day ahead operational planning for the minimization of CO_2 emissions and fuel consumption of an urban microgrid is proposed. This algorithm solves the Unit Commitment Problem (UCP) by the means of a dynamic programming and with predictions of the available energy from PV generators, the power demand from the loads and the State Of charge (SOC) of batteries inside active PV generators.

The second proposed stage is implemented during the day and consists in reducing variations due to the power uncertainty (from the PV production and load demand). An adjustment algorithm corrects, each 30 minutes, references coming from the day ahead operational planning, if changes in forecasted values occur. This adjustment algorithm is based on a sequential quadratic programming method. Both control functions are only possible because of the communication network and the obtained complexity reduction of algorithms coming from the consideration of a cluster of generators and consumers.

This paper is organized as follows. First the concept of AG is recalled. Then general functions for energy management of an electrical system are presented and ordered into the MCEMS for implementation in section III. As emissions and costs of primary energy come from micro gas turbines, manufacturer characteristics are derived to obtain a model useable for optimizations in section IV. Hence, the proposed day ahead operational planning is detailed in section V by adapting the formulation of the UCP to the studied power system then by mathematically expressing constraints and by detailing the application of dynamic programming for the solving. Section VI is focused on the integration of an adjustment procedure during the day in order to erase deviations from the day ahead planning. Finally implementation of this MCEMS for the supervision of an urban microgrid experimented in our laboratory are exposed in the last section. Results from various tested optimization tasks are given to compare obtained CO_2 emissions and costs according to the use of distributed MGTs alone, integration of dispatched PV based active generators with the proposed operational planning and adjustment algorithm.

II. THE CONCEPT OF ACTIVE GENERATOR

To offer new flexibilities concerning power and energy supply to the electrical system, considered AG are based on a 3kW PV generator, 106 Ah batteries and a 160 Farad supercapacitor bank (fig. 3 and 4). All components are connected to a common inner DC bus which is interfaced to the electrical network though a three-phase inverter. The inner instantaneous power balancing and powers dispatching among internal sources and storage units according to the storage level capacity and to the specific requirements/limitations of each source are performed by a Local Controller (LC), whose functions are detailed in [10].

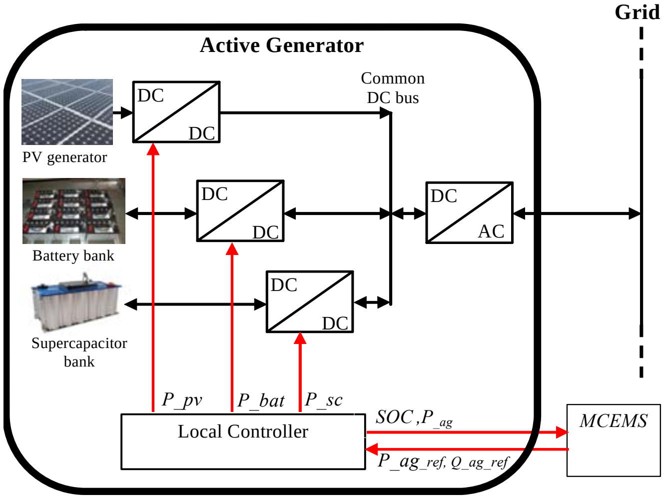

Fig. 3. Scheme of an Active Generator including short and long term energy storage

Real and reactive power references are received from the MCEMS, which receives SOC of batteries and sensed powers at the connection point. Experimental results of the active generator operation, with a 400W power reference (P_{ag_ref}) and power fluctuations from PV panels are presented in fig. 5.

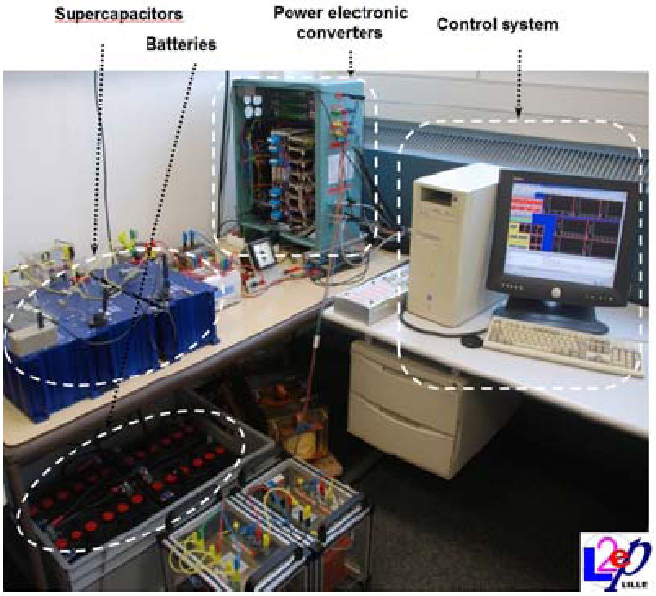

Fig. 4. Actual prototype of the active generator at L2EP laboratory, Lille.

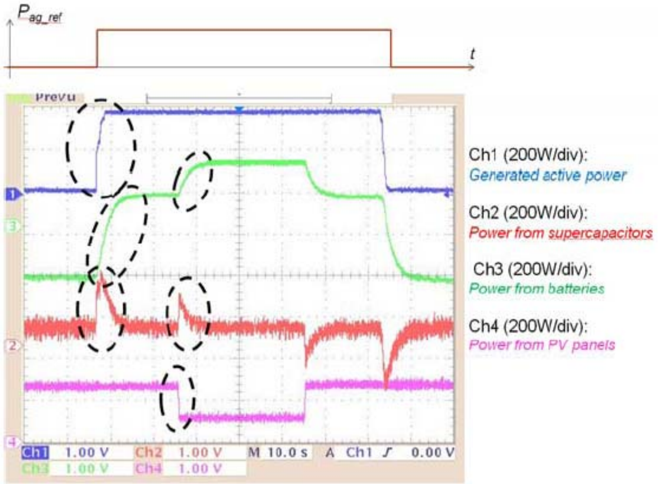

Fig.5. Dynamic power responses under DSO power reference variations

III. MICROGRID CENTRAL ENERGY MANAGEMENT SYSTEM

The MCEMS must assign power references and also other appropriate control signals to the DER units, conventional production units and controllable loads [11]. The goals of the MCEMS algorithm are:

- to ensure uninterruptable power supply to the loads,
- to use the maximum of the REBG energy,
- to minimize the economic costs and the CO_2 equivalent emissions of the gas turbines by setting their power references such, that they produce the minimum pollution and they have minimum start up and shutdowns.

Many difficulties arise. First, the REBG power is variable and meets rarely the power request from the MCEMS. Moreover, there are numerous strategies for managing multiple gas turbines as auxiliary power sources for supplying loads (as example, a strategy may be to use the MGTs having the highest maximum power output as a priority source). Finally, other constraints exist to drive a gas turbine as the minimum power set point, the response time …

The microgrid management is analyzed through various functions that can be classified in a timing scale (fig. 6).

The long-term energy management elaborates a 24 hour-ahead operational planning including:

- the REBG production forecast including the time dependency of the prime source, environmental impacts and cost of generation,
- the management of non-sensitive loads that may be disconnected/shed according to the supervision requirement,
- the provision of an appropriate level of power reserve capacity according to the electricity market and the load demand forecast,
- the maintenance intervals.

The medium-term energy management operates during the day and includes:

- the adjustment of forecasts for the power available from REBG and power demanded by the loads,
- the adjustment of the long-term operational planning, based on deviations in the above mentioned forecasts from those predicted 24 hour-ahead.

The short-term power balancing is performed in the local controllers and includes the primary RMS voltage regulation and the primary frequency control [12], [13].

The long term operation schedule and the energy management can be mathematically expressed as an Unit Commitment Problem (UCP). Due to the complexity of the problem, the required computation time may vary according to used optimization tools but the dynamic programming approach remains a good compromised choice [14].

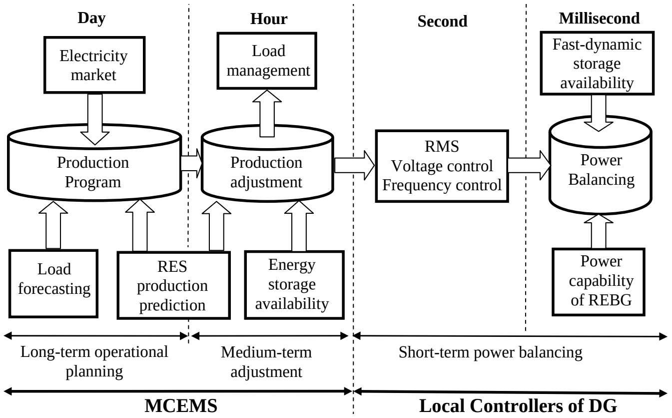

Fig.6. Timing classification of control functions for EMS

IV. CHARACTERIZATION OF MICRO GAS TURBINES

A. Assessment of MGT Fuel Consumption

Fuel consumption of MGT can be assessed using their partial load efficiency characteristics [15-16]. The energetic efficiency between thermal energy (F_{MGT_I} in $kWh_{thermal}$) supplied to the gas turbine combustion chamber and electric energy output (E_{MGT_I} in $kWh_{electric}$) is defined as:

$$\eta_i = \frac{E_{MGT\_i}}{F_{MGT\_i}} \tag{1}$$

The efficiency characteristic is a nonlinear function depending on the partial load ratio:

$$\alpha_i(t) = \frac{P_{MGT\_i}(t)}{P_{MGT\_i\_MAX}} \tag{2}$$

P_{MGT_i} (kW) is the generated MGT electric power, $P_{MGT\_i\_MAX}$ (kW) is the rated MGT electric power.

Based on (1) and (2) the consumed fuel thermal energy for a 30 minutes operation at constant electrical output power is obtained (fig. 7):

$$F_{MGT\_i}(t)=\frac{\alpha_i(t)\,P_{MGT\_i\_MAX}}{\eta_i}1800 \qquad (3)$$

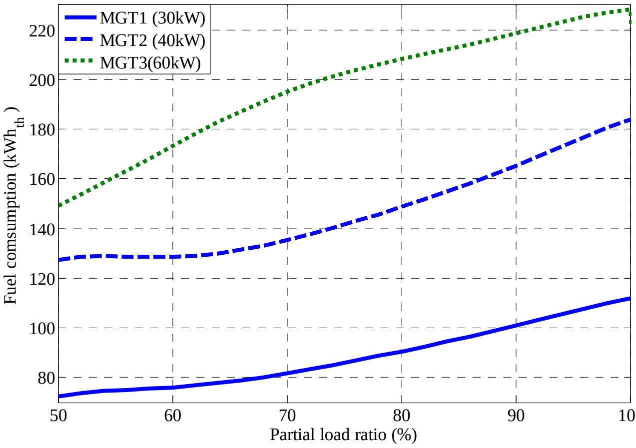

Fig. 7. Fuel power consumption as a function of partial load ratio

By applying a 0,04 €/kWh$_{thermal}$ cost for the consumed gas, the operational cost of each generator (*i*) is obtained from (3) as a function of the generated electric power $P_{MGT\_i}(t)$:

$$C_i = f(P_{MGT\_i}(t)) \qquad (5)$$

B. Assessment of MGT Emissions

The CO_2 equivalent emissions are calculated by applying to the pollutant gases different weights corresponding to their global warming potential [17]. For the assessment of emissions, the masses of the three exhaust gases, NOx, CO and CO_2 are evaluated in g/kWh as a mathematical function of the generated useful power [15], [18], [19]:

$$m_x(t)=\mu_x\,E_{MGT\_i}(t)=\mu_x\,P_{MGT\_i}(t)\,\tau=\mu_x\,\alpha_i(t)\,P_{MGT\_i\_MAX}\,\tau \qquad (6)$$

μ_x (mg/kWh$_{electric}$) is the emission factor (also called specific emissions) for the pollutant x to produce the generic useful electrical energy output E_{MGT_i} and m_x is the mass of the emitted pollutant x. The CO_2 equivalent emissions of each MGT are expressed as a non-linear function of its power output, as presented on fig. 8.

NOx are the most hazardous pollutant gases. The CO emissions are typically very low at full load operation, but are drastically increasing under partial loads, due to incomplete combustion and due to aging of the components or poor maintenance of the equipment. The CO_2 equivalent emissions are related to the global warming potential of MGT exhaust gases. CO and NOx are more dangerous as poison gases, but nevertheless they have a global warming potential, because they are absorbed in the earth's atmosphere slower than CO_2. This means that these gases also contribute to the greenhouse gas effect. Global warming potential has been estimated, according to [17]: 1 gram of NO_x has been considered equivalent to 298 grams of CO_2 and 1 gram of CO equivalent to 3 grams of CO_2. The sum of the three characteristics (CO_2, CO and NOx) according to the MGT partial load ratio, represents the CO_2 equivalent emissions of each micro gas turbine [17] (fig. 8).

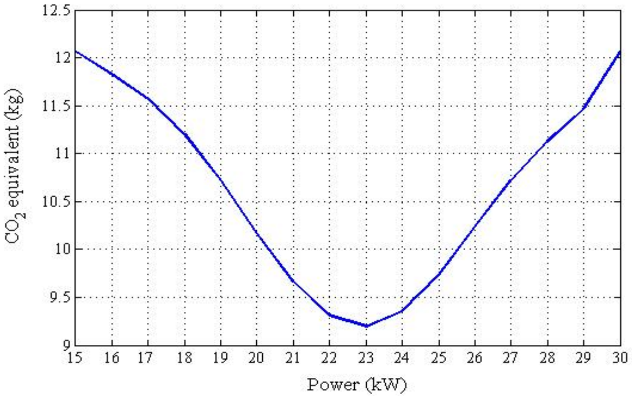

Fig. 8. Characteristic of CO_2 equivalent emissions of a 30kW turbine

In order to apply a multiobjective optimization procedure for a tradeoff between pollutant emissions and consumed fuel price, a price per ton of CO_2 equivalent emissions will be considered. According to economical researches in [20], the historical peak prices for trading a ton of CO_2 emission quota on the european market for industrials is equal to 30 euros. Practical and numerical applications in this paper will be developed with this price.

V. DAY AHEAD OPERATIONAL PLANNING

A. Formulation of the Unit Commitment Problem

For all time steps the operational planning consists in selecting generating units to be used, determining the instant they should be committed and calculating the optimal power references (considered constant during each time step) of each generator.

The general objective of unit commitment is to minimize the total operating cost of an electrical system, while satisfying all of the system constraints. But nevertheless it can be applied to any problem that is expressed in a similar way, such as the minimization of CO_2 equivalent emissions due to power generation. As the power industry goes to new restructured forms, the UCP must be adapted and applied to small DG clusters. So in this paper the UCP is used to formulate and solve our objective functions for cost minimization, emissions reduction and a tradeoff between the two using multiobjective optimization.

The CO_2 equivalent emissions and cost of each generator are expressed as a non-linear function of its power output: $CO_{2\_i}(P_{MGT\_i}(t))\;C_i(P_{MGT\_i}(t))$. Penalties for startup and shutdown of the units are also considered. If the unit will be running in the next period and it is shut down in the current period, a startup penalty is applied. On the other hand, if the unit will not be committed at *t+1* and it is running at *t*, a shutdown penalty is applied. The penalties avoid switching on and off the units because it increases the emissions and shortens the exploitation life of the units. In this study, start-up penalty is considered equal to the consumed fuel cost during 5 minutes operation at full load. Shutdown penalty is considered equal to 2.5 minutes operation at full load. The startup and shutdown penalties for each unit are respectively expressed by functions $C_{pe\_c\_i}(\delta_i(t+1),\delta_i(t))$ and $C_{pe\_co2i}(\delta_i(t+1),\delta_i(t))$. δ_i is the state of each generating unit during each time period (1 if the unit is running or 0 if the unit is shut down).

The 24 hour ahead operational planning is discretized in 48 periods (t) of 30 minutes and power references are considered constant during each period. The two objective functions are defined as:

$$J_C(t)=\sum_{t=1}^{48}\sum_{i=1}^{3}\delta_i(t).C_i(P_{MGT\_i}(t))+C_{pe\_c\_i}(\delta_i(t+1),\delta_i(t)) \qquad (10)$$

$$J_{CO2}(t)=\sum_{t=1}^{48}\sum_{i=1}^{3}\delta_i(t).CO_{2\_i}(P_{MGT\_i}(t))+C_{pe\_co2i}(\delta_i(t+1),\delta_i(t)) \qquad (11)$$

$CO_{2\_i}(P_{MGT\_i}(t))$ are the CO_2 equivalent emissions and $C_{i,t}(P_{MGT\_i}(t))$ is the cost of consumed fuel. $P_{MGT\_i}(t)$ is the generated power, which varies at each time step t. i is the unit number (in our studied system there will be 3 micro gas turbines). Maintenance and management costs are outside of the scope of this paper.

B. *Constraints*

With N active generators and M micro gas turbines, in each discrete time step the power balancing between the loads (P_{LOAD}) and the generators (P_{AG_n} and P_{MGT_i}) must be performed with a maximum use of the "clean" PV energy. This is expressed as an equality constraint:

$$P_{LOAD}(t)-\sum_{n=1}^{N}P_{AG\_n}(t)-\sum_{i=1}^{M}P_{MGT\_i}(t)=0 \qquad (12)$$

The micro gas turbine loading level has to be higher than 50% of the MGT's rated power for improving efficiency and reducing CO_2 equivalent emissions (fig. 9). Moreover the power in reserve must be equal to or larger than 10% of the generator rated power. The corresponding inequality constraint is expressed as:

$$0.5P_{MGT\_\max\_i}\le P_{MGT\_i}\le 90\%P_{MGT\_\max\_i} \qquad (13)$$

A last group of constraints refers to the microgrid operation mode. The constraints differ from one mode of operation to another (day/night, PV power available or not, active generator's battery state of charge) and are detailed in our previous works [21] and [22].

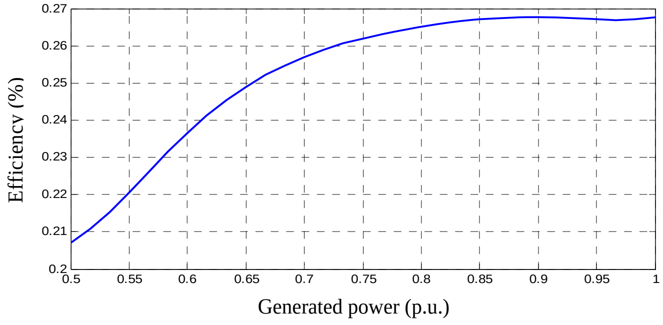

Fig. 9. Efficiency characteristic of a 30 kW gaz microturbine

C. *Application of the Dynamic Programming*

Several approaches can be applied to implement an optimization procedure to solve the UCP by minimizing equ. (10) and (11). Dynamic programming is an exact mathematical and optimization method for solving problems that exhibit properties of overlapping sub problems and optimal substructure. In general, a problem is solved by using a three-step process:

1. Break the problem into smaller recursive sub problems,
2. Solve these problems optimally,
3. Use these optimal solutions to construct an optimal solution path for the problem.

The sub problems are, themselves, solved by dividing them into sub-sub problems, and so on, until a case is enough simple to be solved in constant time. The Bellman equation restates an optimization problem in a recursive form [23], [24]. The optimal solution of the Bellman's recursive equation for all time steps is used to construct the optimal solution of the overall problem.

The principle of dynamic programming is to determine the shortest optimal path starting backwards from the final point by using the Bellman's recursive equation and forecasts of the parameter's values:

$$F_t(t,u(t),x(t))=Tr(F_{t+1},u(t+1),u(t))+F_{t+1}(t+1,u(t+1),x(t+1)) \qquad (14)$$

The system's state variables at step t are the power, generated by the micro gas turbines $x_i(t)=P_{MGT\_i}(t)$ and the control variables are the unit states (0 or 1) $u_i(t)=\delta_i(t)$. F_t and F_{t+1} are the system's operational cost (or emissions) at time steps t and $t+1$ and $Tr(F_{t+1},u(t+1),u(t))$ is the cost of the transition from solution related to the cost F_t to the solution related to the cost F_{t+1}.

The unit commitment problem formulation for the studied system can be expressed in the form of the following recursive dynamic programming equation:

$$F_t=\sum_{i=1}^{3}\left[C_{pe\_c\_i}(\delta_i(t+1),\delta_i(t))+\delta_i(t+1).C_i(P_{MGT\_i}(t+1))\right] \qquad (15)$$

F_{t+1} is the system operational cost at time step $t+1$: $\sum_{i=1}^{3}\delta_i(t+1).C_i(P_{MGT\_i}(t+1))$ and the transition cost from F_t state to F_{t+1} is defined by the sum of startup and shutdown penalties of all generators in the studied system $Tr\,(F_{t+1},u(t+1),u(t))=\sum_{i=1}^{3}C_{pe\_c\_i}(\delta_i(t+1),\delta_i(t))$.

The optimal solution of the overall problem is obtained by selecting the optimal values of control variables in (14) for all time steps recursively from $t=48$ to $t=1$ as depicted fig. 10. The practical implementation of the dynamic programming algorithm for solving the unit commitment problem is presented in detail in previous works [25], [26] and [27].

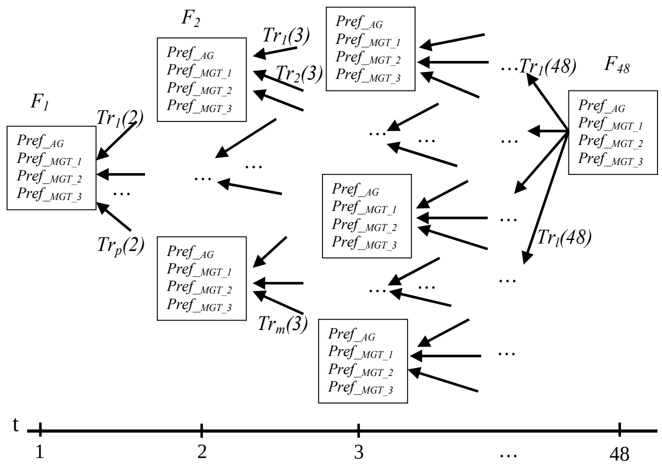

Fig. 10. Principle of optimal path by dynamic programming

VI. MEDIUM TERM ADJUSTMENTS

The AG is capable of maintaining a prescribed power reference, received from the MCEMS, in the limits imposed by the actual State Of Charge (SOC) of the batteries. According to the daily predictions of the available power from the PV ($\tilde{P}_{PV\_24h}$) and the required power of the loads ($\tilde{P}_{Load\_24h}$), a day ahead power production planning for the AG and for micro turbines is determined by the MCEMS. Sometimes the real situation (weather conditions, power demand by loads) could differ from the forecasted values. Current forecasting techniques allow us to have an updated forecast every 30 minutes. During the day the central energy management system refreshes the power references each 30 minutes. In practice, we consider the current forecasted loads ($\tilde{P}_{Load\_t+1}$) and forecasted PV production ($\tilde{P}_{PV\_t+1}$) for the next 30 minutes (time step *t+1*). The 24 hour-ahead forecasted values for time step *t+1* are $\tilde{P}_{Load\_24h\_t+1}$ and $\tilde{P}_{PV\_24h\_t+1}$. The deviation from the day ahead forecasted data is expressed as:

$$\Delta P_{PV\_t+1} = \tilde{P}_{PV\_24h\_t+1} - \tilde{P}_{PV\_t+1} \tag{16}$$

$$\Delta P_{Load\_t+1} = \tilde{P}_{Load\_24h\_t+1} - \tilde{P}_{Load\_t+1} \tag{17}$$

Where $\tilde{P}_{PV\_24h(t+1)}$ and $\tilde{P}_{Load\_24h(t+1)}$ are the day ahead forecasted values of P_{Load} and P_{PV} for time step (*t+1*), ΔP_{PV_t+1} and ΔP_{Load_t+1} are the deviations from the forecasted values.

The medium-term energy management takes into account these deviations by modifying power references of the generators according to the new situation:

$$P_{AG\_ref\_t+1} = \tilde{P}_{AG\_ref\_24h\_t+1} + \Delta P_{PV\_t+1} \tag{18}$$

$\tilde{P}_{AG\_ref\_24h\_t+1}$ is the AG power reference, calculated by the MCEMS day ahead. This management function is similar to the secondary control in large power systems.

A correction in power references for the micro gas turbines in the system is also necessary. A 10% power reserve is scheduled in MGT's power references, so if deviations due to the power unbalancing can be handled by the primary controllers of local controllers. If the deviation from forecasted values is larger than 10%, the algorithm has to switch on a turbine that was not planned to be running at *t+1* in order to compensate the lack of PV power.

VII. VALIDATION OF THE MCEMS AND RESULTS

The studied urban microgrid comprises residential loads, two 30kW micro gas turbines (MGT), one 60kW MGT and twelve homes with 3,6 kW PV based active generators with embedded storage (fig. 11). All power generators and electrical loads are locally connected. So line losses and voltage drops can be ignored. The microgrid central controller measures the microgrid state variables and dispatches, every half of an hour, power references (refreshed by the adjustment algorithm) to micro sources through a communication network. Local controllers (LC) receive these power set points. In the same time they send various data, as example the sensed power production at the coupling point.

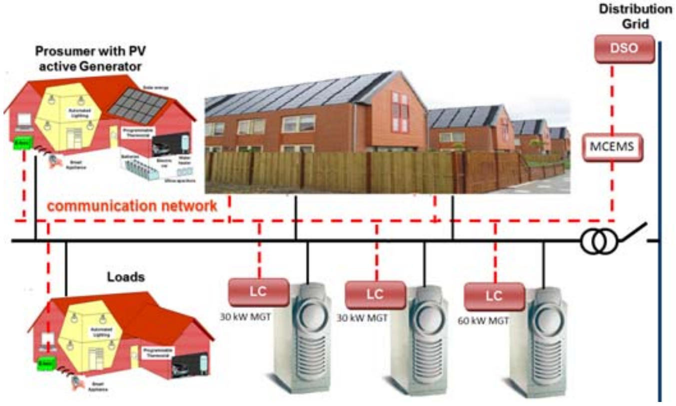

Fig. 11. Schematic diagram of the urban microgrid

The design of the MCEMS requires several simulations working with models of the system in order to validate and optimize the day ahead operational planning and the adjustment algorithm. Additionally, a testing stage in real scenari is required to evaluate the performance of the developed solution and to detect necessary adaptations before it will be implemented in the distribution system. For those reasons, a Real Time - Power Hardware In the Loop (RT - PHIL) application has been developed to validate the AG, the information technologies (application of computers for MCEMS implementation and communication equipment), which are used to store, retrieve, transmit and manipulate data in a realistic scenario with a reduced size and complexity of the testing procedures while increasing the flexibility and reducing the cost of the project (fig. 12 and 13).

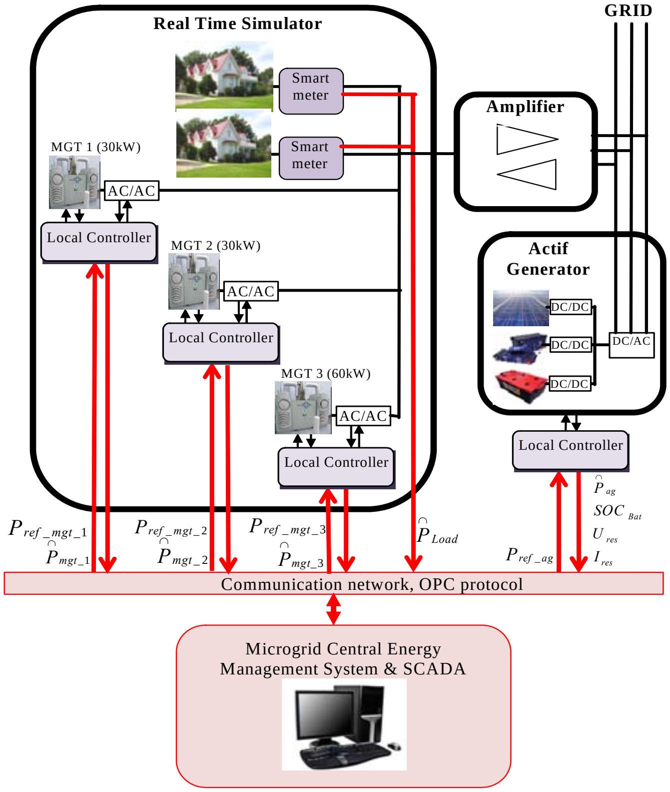

Fig. 12. Schematic diagram of the PHIL

Fig. 13. Overview of the MCEM room at L2EP

The developed PHIL consists in connecting the AG to a power amplifier, which amplifies the output signal of the Real Time Simulator. The feedback loop of the control system is closed by implemented current/voltage measurements at the clamp. Models of the urban network, micro gaz turbines and loads are simulated in real time by the OPAL RT system and are interfaced to the SCADA, which executes the MCEMS.

Various tests have been performed to prove the efficiency of the algorithm for the long-term operational planning, based on the forecasts for available PV power and power demanded to supply the loads (fig. 14). First, a basic dispatching strategy without optimization has been tested. It consist in setting MGT power references proportional to the generator rated power while the added power references corresponds to the remaining power required by loads. Then the optimization procedure has been performed with three different objective functions: to minimize the CO_2 equivalent emissions from the micro-gas turbines, to minimize the consumed fuel or a tradeoff between these two functions. From the results, presented in table I, it is clear that any of the three objective functions causes a reduction of nearly 10 percent in the total operational cost (the cost of CO_2 equivalent emissions plus the cost of consumed fuel), compared to the same system without optimization of the operational planning.

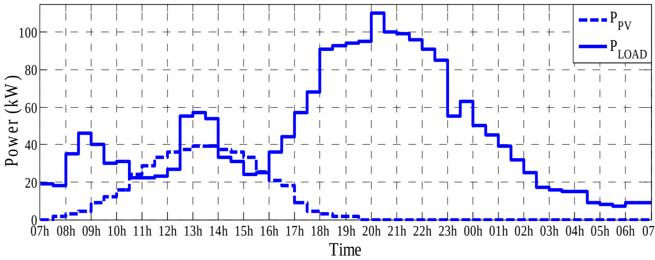

Fig. 14. Day ahead load forecast (kW) and PV power forecast in MPPT (kW)

TABLE I

Day ahead operational planning results from PHIL tests

	CO_2 equivalent	Fuel cost	Total cost
Without optimization	50 €	153 €	203 €
Mono-objective (CO_2 equivalent emissions)	35 € (-30%)	147 € (-4.2%)	181 € (-10.7%)
Mono-objective (Fuel)	36 € (-28.7%)	146 € (-4.6%)	183 € (-10.1%)
Multi-objective	35 € (-29.3%)	147 € (-4.1%)	182 € (-10.3%)

There is not a great difference in the overall cost between the different objective functions because, in fact, the CO_2 equivalent emissions and the consumed fuel are not really independent functions: the fuel consumption is used in the calculation of the CO_2 emissions, which is then used in the calculation of CO_2 equivalent emissions. Thus minimizing either the CO_2 equivalent emissions or the consumed fuel is enough for approximating very well the optimal system operation.

A statistical analysis of sensed power from MGT has been done without optimization and with an optimized operational planning and in the same scenario (fig. 15 and fig. 16). Results prove that the optimization algorithm selects power references such that MGT operate more frequently in the domain between 0.7 and 0.8 p.u. The reason is that operation in this region causes less CO_2 equivalent emissions, as already demonstrated on fig. 8.

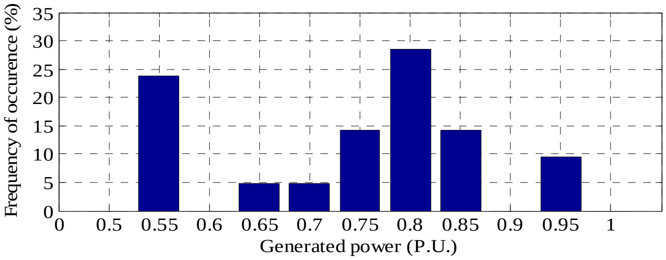

Fig. 15. Occurrence of MGT 2 (30kW) power set points in the scenario without optimization

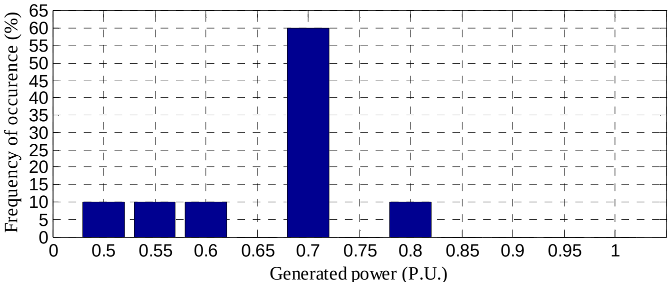

Fig. 16. Occurrence of MGT2 (30kW) power set points using the CO_2 equivalent emissions as objective function

VIII. CONCLUSIONS

Emission reduction and economical optimization of an urban microgrid operation, including dispatched PV-based active generators is presented in this paper. A dynamic programming approach is used for solving the unit commitment problem in the studied microgrid. Based on the load and PV production forecasts, the micro gas turbines characteristics, startup and shutdown penalties for the units and the state of charge of active generators batteries, the algorithm searches by recursion the optimal path through all possible system states in the 24 hour-ahead operational planning. Deviations in forecasted values are compensated by a medium-term adjustment algorithm that recalculates power references for the generators if the difference between day-ahead forecasted values and one hour-ahead forecasts is greater than the 10% power reserve, considered in the operational planning.

The system operation has been tested on a RT-lab real time simulator in a MATLAB/Simulink environment. Four different scenarios have been considered: without optimization of the operational planning and optimization with three different objective functions: minimization of the CO_2-equivalent emissions from the micro-gas turbines, minimization of the consumed fuel or a tradeoff between the two. Results demonstrate that using any of the three objective functions, a reduction of not less than 10 percent in the system total operational cost is achieved, compared to the same system without optimization of the operational planning.

IX. REFERENCES

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