# Environmental and economical optimization of microgrid long term operational planning including PV-based active generators

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***Abstract* — Large scale penetration of Renewable Energy-Based Generators (REBG) and Distributed Energy Resources (DER) requires an evolution of the classical dispatching of conventional generators in power systems. A step towards the Smart Grid is to integrate locally REBG, conventional generators and loads in clusters called microgrids. This paper presents a microgrid energy management optimization in the presence of PV-based active generators. Based on predictions of the available energy from PV generators, energy storage availability and the power demand from the loads, the Microgrid Central Energy Management System (MCEMS) elaborates a 24 hour ahead operational planning using the approach of unit commitment by dynamic programming. The optimization objective function is either the $CO_2$ equivalent emissions (environmental criteria), the fuel consumption (economical criteria) or a tradeoff between these two. In order to reduce uncertainty in forecasted values for PV production or load demand, a medium term energy management recalculates the generators power references one hour ahead if necessary.**

***Keywords* — Microgrid, smart grid, control, renewable energy, distributed energy resources, optimization, emission, cost, reduction.**

## I. INTRODUCTION

In order to ensure a sustainable development, greenhouse gas emissions due to electrical power production have to be reduced. One solution is to use more Renewable Energy Based Generators (REBG). But one of the main problems is the stochastic nature of the energy produced by REBG. Increasing the REBG penetration ratio in power systems could cause difficulties for system operators in matching the power production and demand thus degrading the quality of power supplied to the customers and even further causing interruptions in power supply. A solution to this problem could be a restructuring of the power system architecture. Currently the distribution system is rather passive and centralized from the supervision point of view. With increased penetration of REBG in the power system, the way the whole system is controlled and dispatched should also be revised. A modern power system needs to become "smarter" in order to provide a reliable and sustainable power supply and to maximize the use of REBG thus minimizing dependence on non-renewable resources and greenhouse gas emissions due to electricity generation. The smart grid organization has to incorporate distributed intelligence at all levels of the electric network in order to improve efficiency, reliability and security [1], [2].

The idea of Smart Grid is also to imagine a grid architecture to integrate and control synergy interactions of new components or services with the existing ones.

In this context, the essential problems to overcome are matching the power demand and the production in an optimal way and minimizing the usage of non-renewable resources for electricity generation. A step towards the Smart Grid is to integrate locally REBG, conventional generators and loads in clusters called microgrids. These microgrids will be locally aggregated and controlled by a Microgrid Central Energy Management System (MCEMS) (Fig. 1). The MCEMS itself could perform optimization of the 24 hour ahead local operational planning of energy sources and communicate forecasts for energy excess and/or demand with the Distribution System Operator (DSO) thus facilitating power system dispatching [3], [4].

A solution to the problem associated with stochastic nature of the PV energy is the concept of PV-based Active Generator (AG), which has been already developed and detailed in [5]. It integrates a photovoltaic array with batteries and supercapacitors respectively for long and short term energy storage. By this way, the active generator is capable of delivering constant power to the grid, although in the limits imposed by the Energy Storage Systems (ESS) State Of Charge (SOC) and maximum currents.

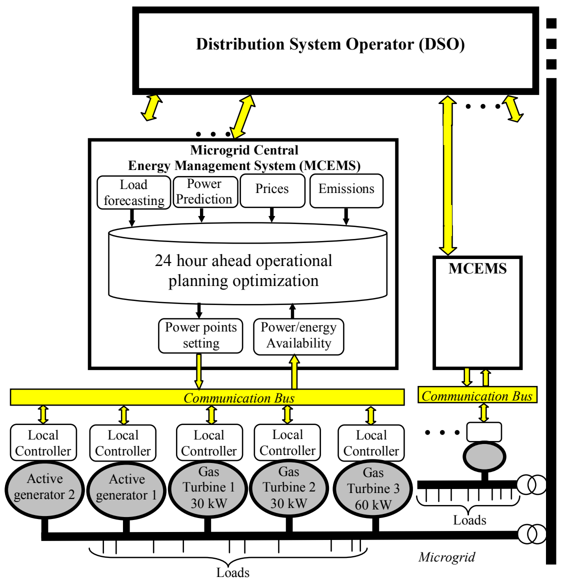


Fig.1. Structure of the studied microgrid in the context of the Smart Grid

In our previous works the organization of a MCEMS and the integration of PV-based generators have been studied [6]. Furthermore a long term energy management optimization algorithm has been designed using a dynamic programming based unit commitment [7].

In this paper, the framework of microgrid control is presented. The long term operational planning of the microgrid is performed by an algorithm including optimization of the unit commitment problem by a dynamic programming approach. This algorithm uses 24 hour-ahead forecasts for the PV power production and power demanded to supply the loads. In a reality there could be deviations from the forecasted values. Therefore an algorithm for medium term energy management is developed in order to recalculate power references for the generators in case of deviations from forecasted values.

The objective of the optimization algorithm can be the cost of the fuel consumed by conventional generators in the system, the $CO_2$ equivalent emissions cost of a tradeoff between these two.

Power generators of the studied microgrid comprise ten PV-based Active Generators (AG), each with 4 kW rated power and three Micro Gas Turbines (MGT) with rated powers of 30, 30 and 60 kW.

## II. Microgrid Central Energy Management System

The task of the MCEMS is to manage the power and the energy between generators and loads into the microgrid. Then the real and reactive power production must be shared among the generators, giving priority to the REBG.

The microgrid management is analyzed through various functions that can be classified in a timing scale presented on Fig. 2. 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 includes:

- the adjustment of the forecasts for power available from the REBG and power demanded to supply the loads,
- the adjustment of the long-term operational planning, based on deviations in the abovementioned forecasts from those predicted 24 hours ahead,

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

## III. The Concept of Active Generator

One of the main drawbacks of actual photovoltaic generators is that the output power fluctuates and depends on weather conditions. Moreover these generators are only capable of delivering the maximum available power. Hence more power than required may be generated and so may induce grid instabilities. Currently experiences show that the maximum penetration ratio of these passive PV generators in European island networks is about to 30%.

One way to increase the penetration ratio is to upgrade actual PV generators in order to transform them into controllable, dispatchable generators. These Active Generators (AG) offer new flexibilities for the grid system operators and consumers. Considered AG's contain batteries for long term energy reserve availability and ultra capacitors for short term power regulation (fig. 3). Thanks to these embedded storage technologies and the dedicated control system, this generator is capable of delivering prescribed power and power system services to the microgrid although it is limited to the energy stored in the batteries [5], [6] and [7]. The real time "Power Balancing" and power dispatching among internal sources and storage units of a DER according to the storage level capacity and to the specific requirements/limitations of sources, including available power from REBG, is performed by the Local Controller.

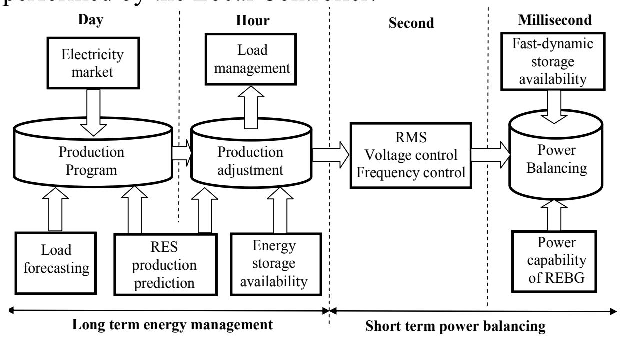


Fig. 2. Timing classification of control functions for EMS

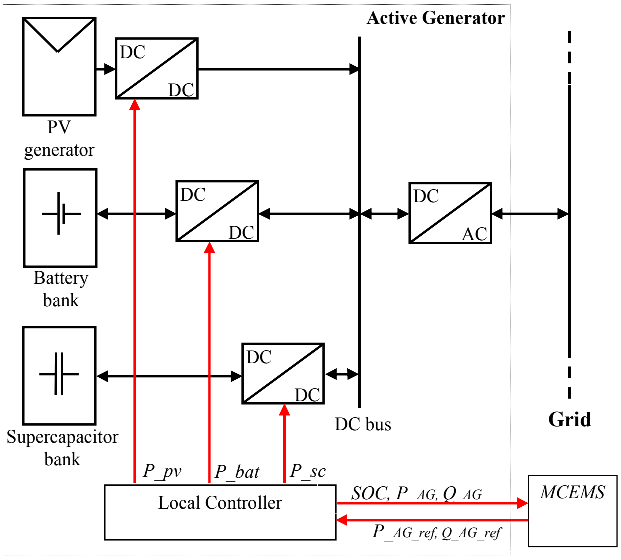


Fig. 3: Scheme of an Active Generator including short and long term energy storage

## IV. Assessment of Micro Gas Turbine Fuel Consumption

Micro Gas Turbines are well suited for distributed generation applications due to their:

- flexibility in connection methods,
- ability to be arranged in parallel to serve larger loads,
- ability to provide reliable power,

- low emission profile.

Micro gas turbines are used also for peak-shaving to reduce electricity generation cost.

Fuel consumption of MGT can be assessed using their partial load efficiency characteristics [8], [9]. The energetic efficiency between thermic energy and electric energy is defined as:

$$\eta_i = \frac{E_{MGT\_i}}{F_{MGT\_i}} \quad (1)$$

Where $F_{MGT\_i}$ (kWhthermic) is the fuel thermal energy supplied to the gas turbine combustion chamber in order to have at the generator side the useful electric energy output $E_{MGT\_i}$ (kWhelectric). This efficiency is not linear in function of the partial load characteristics. The partial load ratio $\alpha_i$ is used:

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

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

Based on (1) and (2) the expression for the fuel thermal energy consumed by the micro gas turbine for 30 minutes operation at constant power is obtained (fig. 4):

$$F_{MGT\_i}(t) = \frac{P_{MGT\_i}(t)}{\eta_i}.\tau = \frac{\alpha_i(t).P_{MGT\_i\_MAX}}{\eta_i}.\tau \quad (3)$$

Where τ=1800s is the time period.

By applying a cost per kWh of fuel thermal energy (example presented on table 1), the MGT operational costs in terms of fuel consumption is obtained. In countries using a non-metric system, fuel thermal energy is often expressed in BTU (British Thermal Unit):

$$1BTU = 0{,}29037Wh \quad (4)$$

With cost per kWh of consumed gas, the operational cost of each generator is obtained from (3) as a function of the supplied power $P_{MGT\_i}(t)$:

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

TABLE 1

RATES OF NATURAL GAS IN FRANCE FOR DOMESTIC USERS [10]

| Annual consumption (MWh_thermic) | <1 | 1< … <6 | >6 |
|---|---|---|---|
| Price ( €/MWh_thermic) | 9,51 | 8,1 | 5,48 |

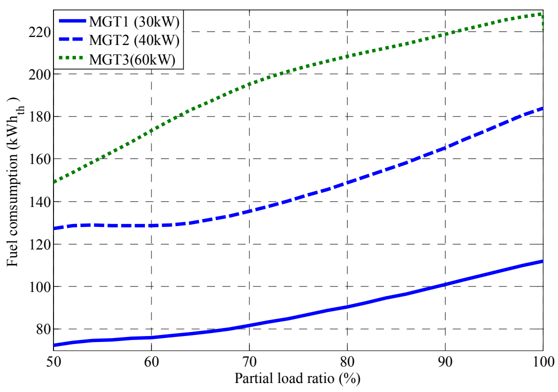


Fig. 4: Fuel power consumption as a function of partial load ratio for the three micro gas turbines in the studied system

V. ASSESSMENT OF MICRO GAS TURBINE EMISSIONS

The $CO_2$ equivalent emissions are calculated by applying to the main pollutants different weights corresponding to their global warming potential [11]. The $CO_2$ equivalent emissions of each Micro Gas Turbine are expressed as a non-linear function of its power output, as presented on fig. 5.

To obtain masses characteristic (g/kWh) of the three exhaust gases: NOx, CO and $CO_2$ are considered as functions of the power output for τ=30 minutes of operation:

$m_{NOx\_i} = f_1(P_{MGT\_i})$, $m_{CO\_i} = f_2(P_{MGT\_i})$ and $m_{CO2\_i} = f_3(P_{MGT\_i})$.

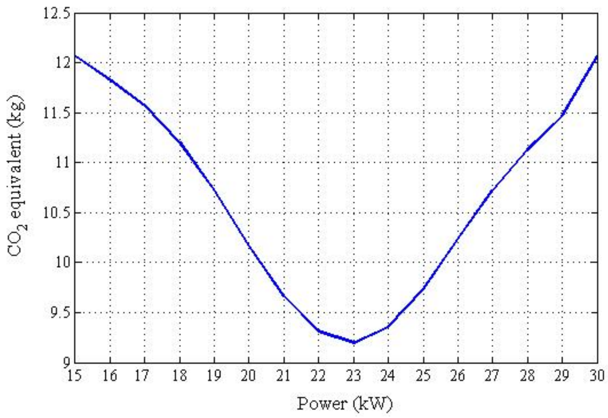


Fig. 5: Characteristic of $CO_2$ equivalent emissions obtained for a 30kW turbine

For the assessment of emissions, the emission factor model is used [9], [12], [13]. According to this model, any gas emission ($CO_2$, CO, NOx etc.) from combustion devices can be evaluated through a mathematical function:

$$m_x(t) = \mu_x.E_{MGT\_i}(t) = \mu_x.P_{MGT\_i}(t).\tau \quad (6)$$

$\mu_x$ (mg/kWhelectric) is the emission factor (specific emissions) for the pollutant $x$ to produce the generic useful electrical energy output $E_{MGT\_i}$ (kWhelectric) and $m_x$ (g) is the mass of the emitted pollutant $x$.

NOx are the most hazardous pollutant gases. For the three gas turbines, the NOx emission factor is expressed in function $F_{NOx\_i}$ of their partial load ratios:

$$\mu_{NOx\_i} = F_{NOx\_i}(\alpha_i) \quad (7)$$

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. As the NOx, the CO emissions are expressed by their emission factor in function of the gas turbine's partial load ratio:

$$\mu_{CO\_i} = F_{CO\_i}(\alpha_i) \quad (8)$$

Following the same method, $CO_2$ emissions are expressed:

$$\mu_{CO2\_i} = F_{CO2\_i}(\alpha_i) \quad (9)$$

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. Thus, their global warming potential can be estimated: according to [11], 1 gram of NOx 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) represents the $CO_2$ equivalent emissions of each micro gas turbine as a function of the produced power, as presented on fig. 5.

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 is considered. This is also done in regard of the future, where it is possible that emission quotas for private persons could exist. According to economical researches in [14], the historical peak prices for trading a ton of $CO_2$ emission quota on the european market for industrials are 30 euros. Therefore practical and numerical applications in this paper will be developed using this price.

## VI. Long Term Energy Management.

The goals of the MCEMS algorithm are:
- to use the maximum of the REBG energy,
- to set power references to all generators, such that the two objectives: minimum $CO_2$ equivalent emissions of the gas turbines and minimum consumed fuel are satisfied.

Many difficulties arise. First, the REBG power does not meet the load curve, also it is not constant during the whole 24 hour ahead optimization period, but the goal is to use it at most. 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 with a high maximum power output as a priority source). Finally, other constraints exist to drive a gas turbine as a minimum power set point, a response time …

The MCEMS must assign power references and also other appropriate control signals to the DER units, conventional production units and controllable loads [15], [16]. The long term operation schedule and the energy management can be mathematically expressed and results to an Unit Commitment Problem (UCP). It can be solved by means of numerous optimization algorithms. Due to the complexity of the problem, the computational time may vary according to different optimization approaches such as: dynamic programming, ant colony optimization, genetic algorithm, exhaustive enumeration, taboo search and others.

### A. *Formulation of the Unit Commitment problem*

The UCP is based on the expression of an objective mathematical function for determining the operation schedule and cost reduction in large power systems. The operation schedule consists in selecting generating units to be used and when they should be committed. The general objective of unit commitment is to minimize the system total operating cost while satisfying all of the system constraints [16]. As the power industry goes restructuring, the UCP will have to be applied to small DG clusters as well as it is done in large power systems comprising many generators of several hundreds or thousands of kW.

The $CO_2$ equivalent emissions of each generator are expressed as a non linear function of its power output $CO_{2\_i}(P_{MGT\_i}(t))$. Penalties for startup and shutdown of the units are applied. The startup and shutdown penalties for each unit are expressed by the function $C_{pe\_c\_i}(\delta_i(t),t))$. $\delta_i$ 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 penalty function adds a certain amount of penalty cost (startup penalty) if the unit is actually off and will be started in the next period. In the same way a shutdown penalty is applied if the unit is committed and will be stopped in the next time period. Startup penalty is considered equal to the cost of consumed fuel and $CO_2$ equivalent emissions during 5 minutes operation at full load. Shutdown penalty is considered equal to the cost during 2.5 minutes operation at full load.

The 24 hour ahead operational planning is discretized in 48 periods (t) of 30 minutes (τ=1800s), considering the power references stay constant during each period. Even if they do not, this is handled by the short-term power balancing functions in the LC integrated in the generators [5]-[7].

The two objective functions are:

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

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

Where $CO_{2\_i}(P_{MGT\_i}(t))$ is the characteristic of the $CO_2$ equivalent emissions. $P_{MGT\_i}(t)$ is the generated power, which varies at each time step *t*. *i* is the unit number (in our studied system there are 3 micro gas turbines). $C_i = f(P(t))$ is the operational cost of each unit in the system (5).

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 ($P_{AG\_i}$ and $P_{MGT\_i}$) must be performed by the MCEMS with a maximum use of the "green" PV energy:

$$P_{LOAD}(t) = \sum_{i=1}^{N} P_{AG\_i}(t) + \sum_{i=1}^{M} P_{MGT\_i}(t) \tag{12}$$

The constraints include also the micro gas turbine loading level, which has to be more than 50% of the MGT's rated power for improving efficiency and emissions reduction:

$$P_{MGT\_i} \in [0.5,\ 1]P_{MGT\_i\_\max} \tag{13}$$

The third group of constraints refers to the microgrid operation mode. The constraints differ from one mode of operation to another (amount of power demanded to supply the loads, PV power available or not, active generator's battery state of charge) and are detailed in our previous works [5], [6]. The framework of the algorithm used for calculation of optimal power references for one time step is presented on fig.6.

### B. *The Dynamic Programming approach to solve the unit commitment problem.*

There are several approaches to implement an optimization procedure. One approach is an exact mathematical optimization procedure called "*dynamic programming*". Dynamic programming is a method for solving problems that exhibit the properties of overlapping sub problems and optimal substructure. In some cases this method takes much less computing time than other methods.

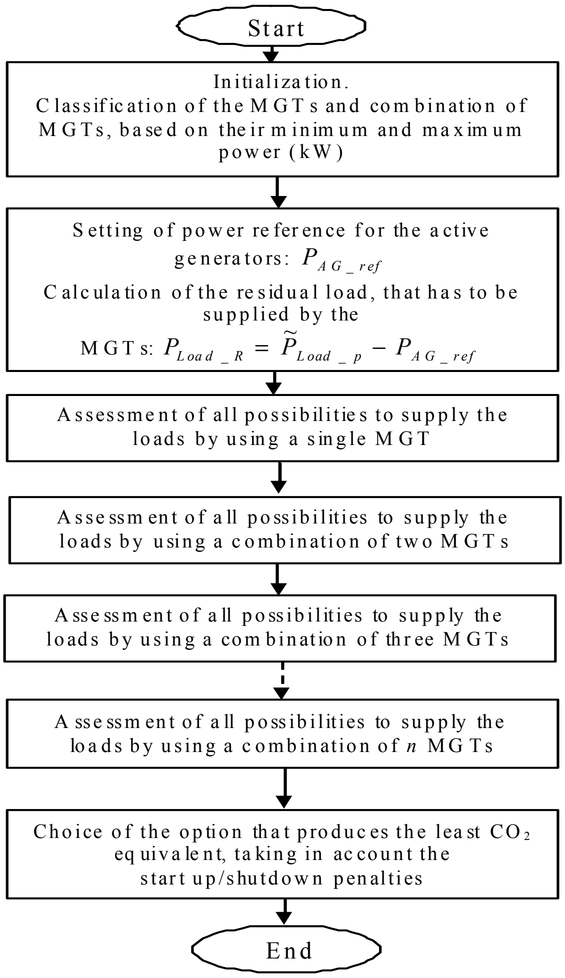


Fig. 6: Framework of the algorithm used for calculation of optimal power references for one time step

The term was originally used in the middle of the 20th century by Richard Bellman to describe the process of solving problems where one needs to find the best decisions one after another. The Bellman equation restates an optimization problem in recursive form [17]. The solution of Bellman's recursive equation (also known as a dynamic programming equation) (14) for all of the time steps is the optimal solution of the problem. Optimal solutions of these subproblems are used to find the optimal solution of the overall problem by recursion, as presented on fig. 7.

Solving the general problem recursively is of crucial importance, because, when starting from the beginning the first suboptimal solution will not always lead to a global optimal path to the final state. In general, a problem can be solved with optimal substructure using a three-step process:

1. Break the problem into smaller sub problems.
2. Solve these problems optimally using recursion (14).
3. Use these optimal solutions to construct an optimal solution for the original problem.

Recently the dynamic programming principles have been applied to solve the unit commitment problem in large power systems [18], [19]. There are different approaches to solve the UCP by dynamic programming. In our work, the objective is the determination of the number of units committed to supply the loads for all time steps in the operational schedule of a microgrid.

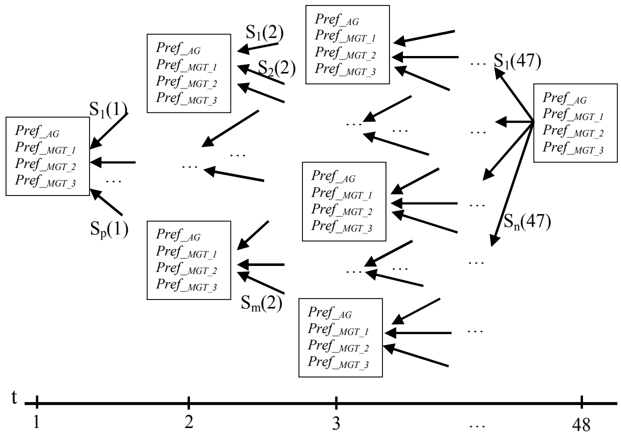


Fig. 7: Illustration of the principle of optimal path by dynamic programming

Nevertheless there are two main approaches for applying dynamic programming to solve the UCP.

The top-down approach: The problem is broken into sub problems, which are solved and the solutions are remembered, in case they need to be solved again. This is a recursion and a memorization combined together.

The bottom-up approach: All sub problems are solved in advance and then are used to build up solutions to larger problems. This approach implies a smaller stack space and less function calls, but sometimes it is not intuitive to figure out all the sub problems needed for solving the given problem [19], [20]. In the present work we use the top-down approach.

The optimality principle says that the optimal trajectory (policy) is the one that minimizes the objective function with regard of the resulting steps, starting backwards from the final state. So, according to the Bellmann's recursive equation, for our problem the objective function is expressed as:

$$F(S(t)) = \min\{S(t) + F(S(t+1))\} \quad (14)$$

$F(S(t+1))$ is the suboptimum function for the $S(t+1)$ time step, $S(t)$ is the amount of emissions or consumed fuel (10) or (11) respectively.

## VII. MEDIUM TERM ENERGY MANAGEMENT

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 daily predictions of the available power and energy from the PV ($\tilde{P}_{PV\_24h}$) and the required power and energy of the loads ($\tilde{P}_{Load\_24h}$), a power production planning for the AG and for the micro turbines is determined by the MCEMS. The central energy management system refreshes the power references each 30 minutes. If the available PV power is greater than the power demanded by the MCEMS, the excess is stored in the batteries. When no PV power is available, power stored locally in the batteries can be used to satisfy the power request if their SOC is sufficient for this.

Power references from the long-term energy management are calculated by the MCEMS with a 24-hour ahead planning from the load and PV production forecasting. Sometimes the real situation (weather conditions, power demand by loads) are different from the forecasted conditions. Current forecasting techniques allow us to have an updated forecast every 30 minutes. In practice, we consider the current forecasted loads ($\widetilde{P}_{Load\_t+1}$) and forecasted PV production ($\widetilde{P}_{PV\_t+1}$) for the next half of an hour (time step $t+1$). The 24 hour-ahead forecasted values for time step $t+1$ are $\widetilde{P}_{Load\_24h(t+1)}$ and $\widetilde{P}_{PV\_24h(t+1)}$. The deviation from the 24h-ahead forecasted data is expressed as:

$$\Delta P_{PV\_t+1} = \widetilde{P}_{PV\_24h(t+1)} - \widetilde{P}_{PV\_t+1} \quad (14)$$

$$\Delta P_{Load\_t+1} = \widetilde{P}_{Load\_24h(t+1)} - \widetilde{P}_{Load\_t+1} \quad (15)$$

Where $\widetilde{P}_{PV\_24h(t+1)}$ and $\widetilde{P}_{Load\_24h(t+1)}$ are the 24-ahead forecasted values of $P_{Load}$ and $P_{PV}$ for time step ($t+1$), $\Delta P_{PV\_t+1}$ and $\Delta P_{Load\_t+1}$ 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. This operating is similar to the secondary control in large power systems. Here the refreshing of power references for the active generator is done each half of an hour by the MCEMS:

$$P_{AG\_ref\_t+1} = \widetilde{P}_{AG\_ref\_24h\_t+1} + \Delta P_{PV\_t+1} \quad (16)$$

Where $\widetilde{P}_{AG\_ref\_24h\_t+1}$ is the AG power reference, calculated by the MCEMS 24 hour-ahead. A correction in power references for the micro gas turbines in the system is then induced. Normally the power that has to be delivered by the MGT's (the residual load) for every 30-minute time step is $\widetilde{P}_{Load\_R\_24h\_t+1}$. When deviations in $P_{AG\_ref\_t+1}$ or $P_{Load\_t+1}$ occur, a new set point of the residual load is calculated:

$$P_{Load\_R\_t+1} = \widetilde{P}_{Load\_R\_24h\_t+1} + \Delta P_{Load\_t+1} - P_{AG\_ref\_t+1} \quad (17)$$

This power has to be delivered by the Micro Gas Turbines (or other conventional sources) in the system, following the algorithm presented in our previous studies [ISGT 2011]. In the algorithm, there is a 10% reserve in MGT's power references, so if the deviation in $\widetilde{P}_{Load\_24h\_R\_t+1}$ is less than 10%, corrections in MGT power references can be handled by the local controllers. In other words, if (18) is true, power references for time step *(t+1)* are recalculated by the local controllers, integrated in the MGT:

$$\left| \frac{P_{Load\_R\_t+1} - \widetilde{P}_{Load\_24h\_R\_t+1}}{\widetilde{P}_{Load\_R\_24h\_t+1}} \right| \leq 0{,}1 \quad (18)$$

If inequality (18) is not true, power references for ($t+1$) have to be recalculated by the medium term energy management. The medium term control algorithm is presented on fig. 8.

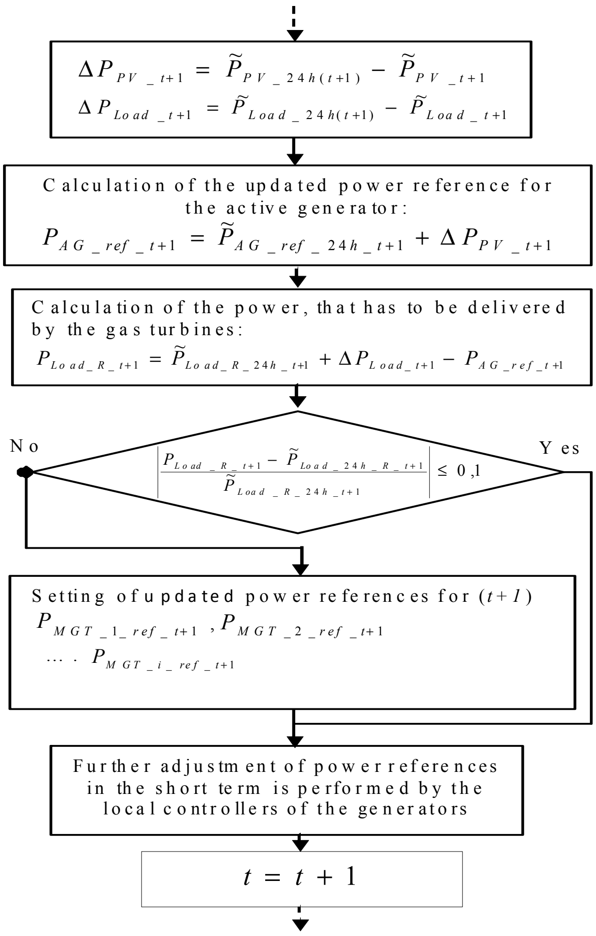


Fig. 8. Algorithm for medium-term control of a microgrid

## VIII. Optimization Results

A model of the studied system is created in MATLAB/Simulink. It comprises three micro gas turbines with rated powers of 30, 40 and 60 kW and ten PV-based active generators, each with peak power of 4kW.

Based on the 24-ahead forecasts for available PV power and power demanded to supply the loads (fig. 9), the objective function to be minimized is the consumed fuel. The optimization results in a 24-hour ahead operational planning with 30 minute power references for each generator in the studied system. Four simulations were made. One without optimization, for comparison and three with different objective functions: the $CO_2$ equivalent emissions, the consumed fuel and a tradeoff between the two by using multiobjective optimization (table 2). On fig. 10-13 are presented the resulting power references when using the consumed fuel as objective function.

From the results, presented on table 2 can be noticed, that by applying the optimization procedure, the total overall cost is around 14% lower than without using optimization. There is not a great difference in overall cost between the different objective functions. When using multiobjective optimization, the overall cost is actually higher than in the case using only one of the objective functions. This is due to the fact that the two objectives are not really independent functions: the fuel consumption is used in the calculation of the $CO_2$ emissions, thus the algorithm cannot find a compromise between these two objectives.

On fig. 10 the total available PV power is greater than the power demanded to supply the loads between 10:30 and 12:00 and also between 14:00 and 15:30. In this case the excess energy is stored in the batteries of the active generators and then it is used to supply the loads in the night (between 4:30 and 7:00 on fig. 10), without having to switch on any of the micro gas turbines.

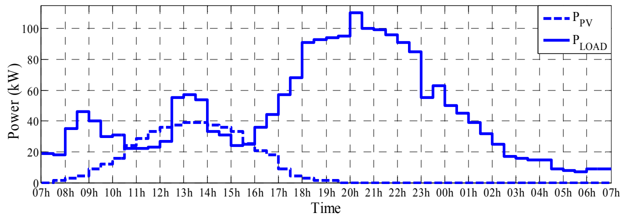


Fig. 9: 24 hour load forecast (kW) and PV power forecast in MPPT (kW)

TABLE 2
OPTIMIZATION RESULTS FOR THE 24 HOUR AHEAD OPERATIONAL PLANNING

| Optimization type | Fuel cost | Emissions cost | Total cost |
|---|---|---|---|
| Without optimization | 215.62 € | 49.73 € | 265.35 € |
| Mono-objective (fuel) | 197.90 € | 33.62 € | 231.52 € |
| Mono-objective (emissions) | 198.83 € | 33.58 € | 232.40 € |
| Multiobjective | 198.87 € | 34.27 € | 233.14 € |

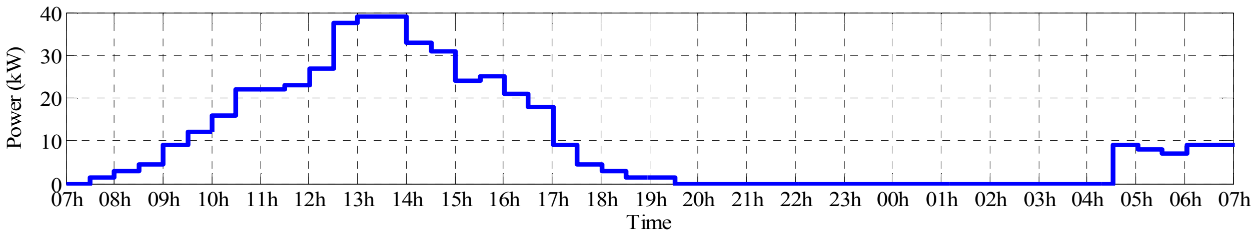


*Fig. 10: Calculated power references for the active generators*

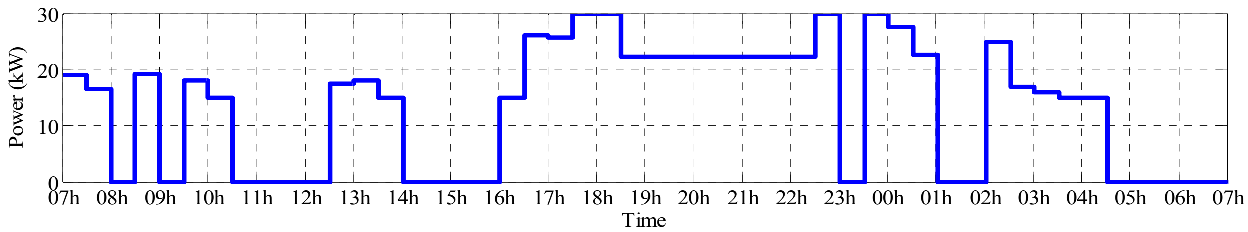


*Fig. 11: Calculated power references for Micro gas turbine 1 (30kW Maximum power output)*

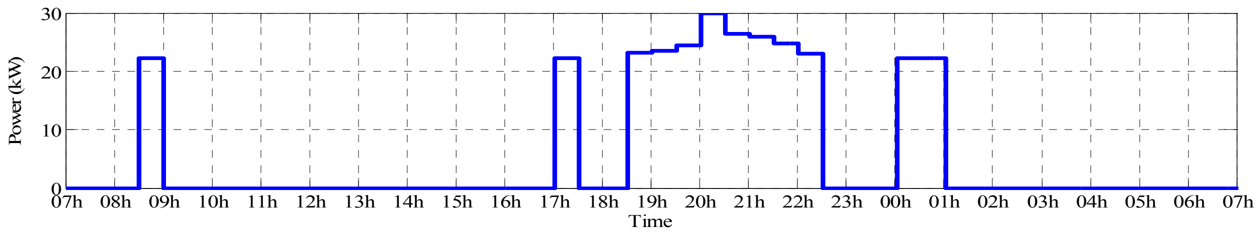


*Fig. 12: Calculated power references for Micro gas turbine 2 (30kW Maximum power output)*

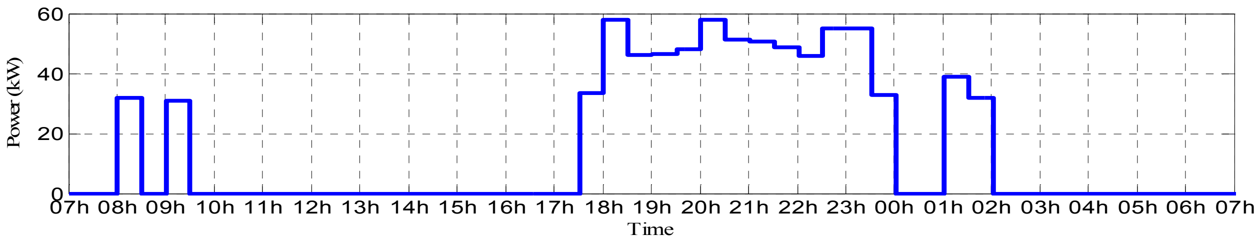


*Fig. 13: Calculated power references for Micro gas turbine 3 (60kW Maximum power output)*

## IX. CONCLUSIONS

Environmental and economical optimization of microgrid long term operational planning is presented in this paper. Based on 24 hour ahead predictions for available PV power and power, demanded to supply the loads, an algorithm for unit commitment by dynamic programming performs the optimization. Priority is given to the pollution-free power from PV-based active generators. If the PV power is greater than the power, demanded to supply the loads, it is stored in the active generators batteries and used at a later time. The objective functions are either the $CO_2$ equivalent emissions (environmental criteria), the consumed fuel (economical criteria) or a compromise between these two. Simulation results show that using an optimization procedure, a cost reduction of 15% is achieved for 24 hours operation of the system.

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