Unit commitment by dynamic programming for microgrid operational planning optimization and emission reduction

H. Kanchev, B. Francois *Senior Member, IEEE*, and V. Lazarov

***Abstract*-- This paper presents a 24 hour ahead microgrid power planning using the approach of unit commitment by dynamic programming. The studied system comprises twelve PV-based active generators with embedded storage and three micro gas turbines. Based on the prediction of the energy available from the PV generator, the storage availability, the micro turbine emission characteristics and the load prediction, a central energy management system calculates a 24-hour ahead plan of the power references for three micro gas turbines and the active generators in order to minimize the CO_2 equivalent emissions of the gas turbines.[1]**

***Index Terms*-- Smart grid, micro grid, renewable energy, optimization, emissions minimization, energy management, dynamic programming, unit commitment.**

I. Introduction

One of the main challenges in the last decades is the need to reduce pollutant gas emissions and dependence on fossil fuels. This leads to a large penetration of renewable energy based generators in power systems [1], [2]. In the past electricity was produced mainly in large-scale power plants, therefore electrical systems have been designed mainly for unidirectional energy flows from large power plants to consumers. In the recent years the amount of Distributed Energy Resources (DER) being connected to power systems has increased. This implies considerable research activity on the integration and control of electrical systems comprising large amounts of DER. Although, in the upcoming years, an even greater increase of Renewable Energy Based Generators (REBG) is expected. But the power available from these generators is dependent on the weather forecast and does not always meet the load curve, which causes difficulties to Distribution System Operators (DSO).

The attention is now oriented toward the use of DER for improving grid operation by contributing to ancillary services, increasing the energy reserve and reducing CO_2 emissions. In practice, new facilities are expected to reduce congestion, to minimize the production cost and to maintain the frequency and voltage. These developments require a fundamental redesign of the grid control. To maximize the use of renewable energy based generators a cluster of small-scale power generators has to be locally aggregated and controlled by a Microgrid Central Energy Management System (MCEMS). An example of architecture (also called Smart Grid) is presented on fig.1. The MCEMS apart from controlling and optimizing the local microgrid operation will communicate with the DSO thus helping to facilitate large scale power plants dispatching and further reducing pollution [3], [4] and [5]. The objective of the MCEMS is to manage locally the power production and demand in order to match them in an optimal way. This implies several limitations as:

- the power availability of REBG,
- the power production and demand balance,
- the optimal loading level of micro gas turbines,
- the minimization of micro turbine startups and shutdowns.

Communication can help the MCEMS and the DSO take advantage of the full potential of renewable energy based generators, microgrid operational planning and also facilitate large-scale power plant dispatching.

The Unit Commitment Problem (UCP) consists in selecting the generating units to be used during a scheduling period. The overall problem is divided into sub problems, which are solved consecutively. There are numerous approaches to solve the UCP such as: priority listing, mixed integer programming, particle swarm optimization, dynamic programming, artificial neural networks, genetic algorithm and others [6], [7].

In this paper the dynamic programming is implemented to solve the UCP and to minimize the CO_2 equivalent emissions in the studied microgrid.

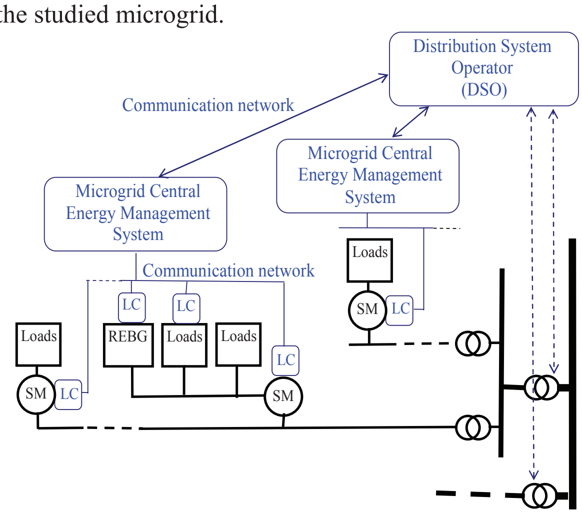

Fig. 1: A microgrid based architecture for smart grid applications

[1] This research is financially supported by the Bulgarian National Research Fund - contract DUNK-01/3 in the framework of the University Research Complex - Technical University of Sofia.

II. The Concept of Active Generator (AG)

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 possible 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 generators. These active generators (AG) offer new flexibilities for the grid system operators and consumers. Active generators contain batteries for long term energy reserve availability and ultra capacitors for short term power regulation (fig. 2) [8]. 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.

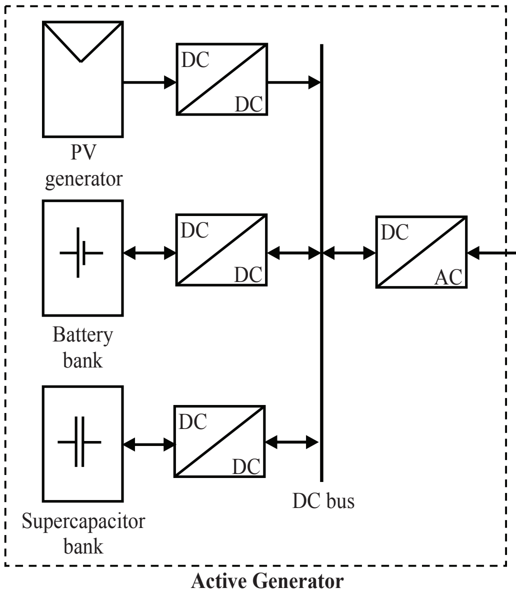

Fig. 2: Scheme of an Active Generator including short and long term energy storage

III. Structure of the Studied Microgrid

The studied microgrid (fig. 3) includes residential loads, 12 PV-based active generators and three micro gas turbines with 30kW, 40kW and 60kW rated power outputs. A communication network is set up between the power equipments and the MCEMS, allowing it to send power references to the generators and to exchange data. The active generators are situated close to each other, have similar characteristics and so they are aggregated by the MCEMS as a single 36 kW active generator.

The global objective consists in matching the total power production to demand in an optimal way [9], [10]. This concept is pertinent in the framework of smart grids through the combined use of an additional communication network within an intelligent energy management system and local controllers [11]. This scheme is a step between current grid requirements and future smart grids.

In our previous works the organization of a microgrid energy management, the integration of photovoltaic active generators have been studied [8], [12]. A multi-objective optimization for long term operational planning has been implemented in order to reduce pollutant emissions [13]. Using this algorithm, a 9% reduction of CO_2 equivalent emissions over a 24 hour operational planning has been achieved. This algorithm optimizes the operational planning for every single discrete time period without taking into account the future system states and the turbine generator startup and shutdown penalties. To improve this algorithm, a unit commitment by dynamic programming algorithm is proposed in this paper.

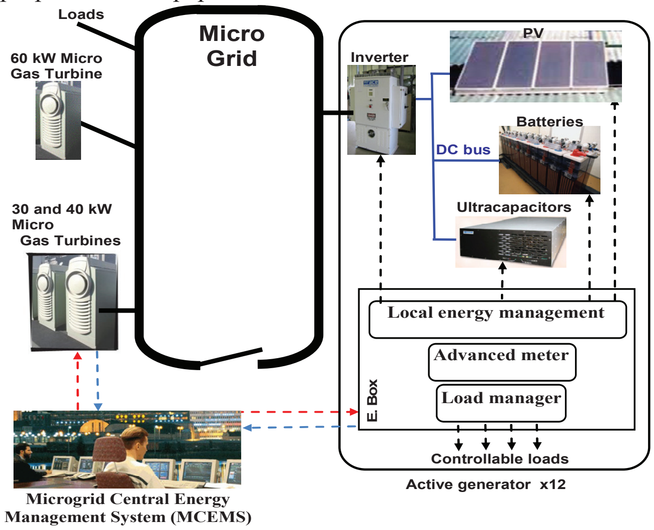

Fig. 3: Microgrid including 12 active generators, 3 gas turbines and a central energy management

IV. Assessment of the CO_2 Equivalent of Micro Gas Turbine Emissions.

The CO_2 equivalent emissions of each Micro Gas Turbine (MGT) are expressed as a non linear function of its power output $C_{i,t} = f(P_{MGT\_i}(t))$ (fig. 4). To obtain such a characteristic, masses (g/kWh) of the three main pollutants: NOx, CO and CO_2 are considered as functions of the power output for 30 minutes of operation:

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

$m_{CO2\_i} = f_3(P_{MGT\_i})$.

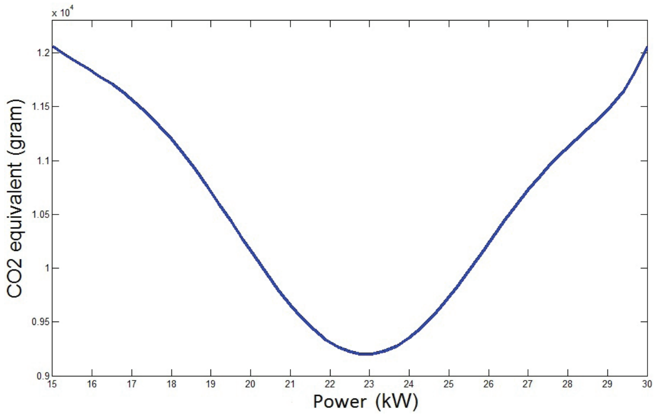

Fig. 4: CO_2 equivalent emissions obtained for a 30kW turbine

The fuel consumption represents the energy efficiency goal. In economic terms, it also corresponds to the minimization of the system's operating costs [14]. In addition, as the three gas turbines use the same fuel (natural gas), the minimization of fuel consumption corresponds approximately to the minimization of CO_2 emissions [14], [15]. The relevant aspect here is that costs and CO_2 emissions are not conflicting objectives under the considered hypotheses in this study.

The energetic efficiency of a MGT is expressed as:

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

F_{MGT_i} ($kWh_{thermic}$) is the fuel thermal energy supplied to the gas turbine in order to produce the useful electric energy output E_{MGT} ($kWh_{electric}$). The fuel consumption of one micro gas turbine during the time τ can be estimated with the following equation:

$$F_{MGT\_i} = \frac{\alpha_i . P_{MGT\_i\_MAX}}{\eta_i}.\tau \quad (2)$$

$P_{MGT\_i\_MAX}$ is the rated power of micro turbine *i*. α_i (%) is the loading level of the micro turbine and is assumed to be constant during the duration τ:

$$\alpha_i = \frac{P_{MGT\_i}}{P_{MGT\_i\_MAX}}.100\% \quad (3)$$

For the assessment of emissions, the emission factor model is used [14], [15], [16]. According to this model, any pollutant emission (CO_2, CO, NOx etc.) from combustion devices can be evaluated through a mathematical function:

$$m_x = \mu_x . E_{MGT\_i} \quad (4)$$

μ_x is the emission factor (specific emissions) for the pollutant *x* to produce the generic useful electrical energy output E_{MGT_i}. m_x [$mg/kWh_{thermic}$] is the mass of the pollutant *x*, emitted to produce the useful electrical energy *E* ($kWh_{electric}$).

The CO_2 emission characterization can be derived from equation (4). The usual approach is to consider the emission factor μ_{CO2} to be equal to 202 $g/kWh_{thermic}$, referred to the thermal energy *F*($kWh_{thermic}$) generated by burning the fuel as input to the gas turbine [18]. By applying this method the mass of CO_2 emissions is obtained:

$$m_{CO2} = \mu_{CO2}.F_{MGT\_i} = \mu_{CO2}.\frac{\alpha_i . P_{MGT\_i\_MAX}}{\eta_i}.\tau \quad (5)$$

With equations (1), (2) and (3), the efficiency of the three micro turbines can be expressed in function of their load using their partial-load characteristics.

NOx are the most hazardous pollutant gazes. For the three gas turbines, the NOx emission factor is expressed in function F_{NOx_i} of their loading levels:

$$\mu_{NOx\_i} = F_{NOx\_i}(\alpha_i) \quad (6)$$

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 loading level:

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

In order to calculate the quantities of equivalent CO_2 emissions, 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 [17], [18]. The sum of the three characteristics represents the CO_2 equivalent emissions of each micro gas turbine as a function of its loading level (produced power), as presented on fig. 4.

V. UNIT COMMITMENT BY OF DYNAMIC PROGRAMMING APPROACH.

A. Formulation of Unit Commitment

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 [6], [7]. As the power industry goes restructuring, the UCP will have to be applied to small DG clusters as well as in large power systems comprising many generators of several hundreds or thousands of kW. UCP focuses of fuel consumption and cost minimization, but nevertheless it is considered applicable to any problem that can be expressed in a similar way. In this paper the UCP is used to formulate and solve our objective function not for cost minimization, but for emissions reduction.

The CO_2 equivalent emissions of each generator are expressed as a non linear function of its power output $C_{i,t}(P_{MGT\_i}(t))$, as described in paragraph IV. Furthermore, penalties for startup and shutdown of the units are considered. The 24 hour ahead operational planning is discretized in 48 periods (*t*) of 30 minutes (τ), considering the power references stay constant during each period. Or even if they do not, this is handled by the short-term power balancing functions in the LC integrated in the generators, as described in [12].

The amount of emissions in a time step (t) is given by the equation:

$$S(t) = \sum_{i=1}^{3} (\delta_i(t).C_i(P_{MGT\_i}(t),t) + C_{pe\_i}(\delta_i(t),t) \quad (8)$$

$C_{i,t}(P_{MGT\_i}(t))$ is the function 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). 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 startup and shutdown penalties for each unit are expressed by the function $C_{pe\_i}(\delta_i(t),t$.

The objective function for the whole system is to minimize the total amount of emissions after a 24 hour operation:

$$f = \sum_{t=1}^{48} S(t) \quad (9)$$

Due to the embedded battery and supercapacitor storage, the PV-based active generator in the system is capable of delivering prescribed power without fluctuations, in the limits imposed by the battery and supercapacitor state of charge. During the day, for time steps when the load power demand is less than the available PV energy, the local energy management inside the active generator stores the excess PV energy in the batteries. Then they can be discharged during the night with the goal of using the micro gas turbines at the operating point, which produces the minimum pollutant emissions. This implies several operating modes of the microgrid, in function of the PV power availability and the load forecast. Our goal is to maximize the benefits of the clean and non-polluting energy source. In the presence of *N* active generators and *M* micro gas turbines in a microgrid, during each discrete time step (*t*) the power balancing between the power, demanded to supply the loads in the system (P_{LOAD}) and power produced by the generators (P_{AG_i} and P_{MGT_i}) must be performed by the MCEMS with a maximum use of the "clean" PV energy:

$$P_{LOAD}(t) = \sum_{i=1}^{N} P_{AG\_i}(t) + \sum_{i=1}^{M} P_{MGT\_i}(t) \quad (10)$$

B. Dynamic Programming

There are several approaches to implement an optimization procedure. One approach is an exact mathematical optimization procedure called "*dynamic programming.*" In mathematics and computer science, dynamic programming is a method for solving problems that exhibit the properties of overlapping sub problems and optimal substructure (described below). The method takes much less time than naive methods.

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 [21]. The solution of Bellman's recursive equation (also known as a dynamic programming equation) (11) 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. For example, the shortest path to a goal from a vertex in a graph can be found by first computing the shortest path to the goal from all adjacent vertices, and then using this to pick the best overall path, as shown in fig. 5. Solving the general problem recursively is of crucial importance, because as illustrated on fig. 5, 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 this three-step process recursively.
3. Use these optimal solutions to construct an optimal solution for the original 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 a constant time. Recently the dynamic programming principles have been applied to solve the unit commitment problem in large power systems or to optimize the use of distributed storage in electrical grids [7], [20] and [22]. There are different approaches to solve the UCP by dynamic programming. For example, in [20], [23] and [24] the approach, is to find the optimal combination of units committed to supply *X* MW of power during a single time step (i.e. the sub problems are of the type "what is the optimal number of units to supply *X-Y* MW and so on until the optimum combination of units to supply *X* MW is reached). In our work, the objective is the determination of the number of units committed to supply the loads for every time step in the operational schedule of a microgrid.

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 [23]. In the present work we use the top-down approach.

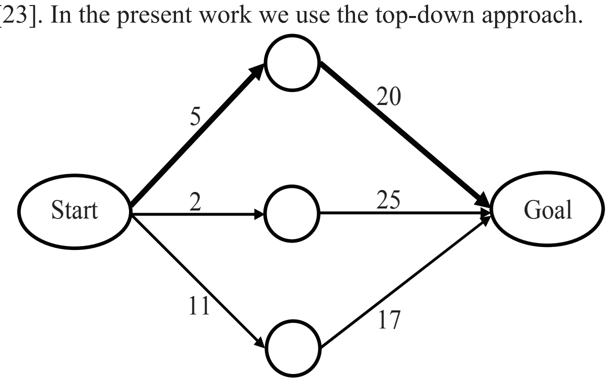

Fig. 5: Illustration of the principle of optimal path by dynamic programming

C. Application to the Unit Commitment Problem

The principle of dynamic programming is to determine the shortest optimal path starting backwards from the final point by using the Bellmann's recursive optimality equation. 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, for our problem, the objective function is expressed as:

$$F(S(t)) = \min\{S(t) + F(S(t+1))\} \quad (11)$$

$F(S(t+1))$ is the suboptimum function for the $S(t+1)$ time step, $S(t)$ is the amount of emissions (equation 8).

The optimization constraints include the production and demand power balance (10) and the micro gas turbine loading level, which has to be more than 50% of the MGT's rated power for efficiency constraint and emission reduction:

$$P_{MGT\_i} \in [0.5 P_{MGT\_i\_\max}, P_{MGT\_i\_\max}] \quad (12)$$

The third group of constraints refers to the microgrid operation mode. The constraints differ from one mode of operation to another one (day/night, PV power available or not, active generator's battery state of charge) and are detailed in our previous works [12] and [13].

VI. RESULTS.

In the Matlab model of the studied system a unit commitment by a dynamic programming algorithm for microgrid central energy management optimization is implemented. The model has two inputs: the 24 hour ahead PV power forecast and load power demand forecast (presented on fig. 6 and 7).

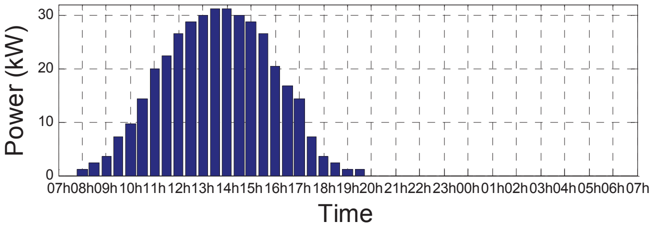

Fig. 6: 24 hour ahead PV production forecast for the 12 active generators

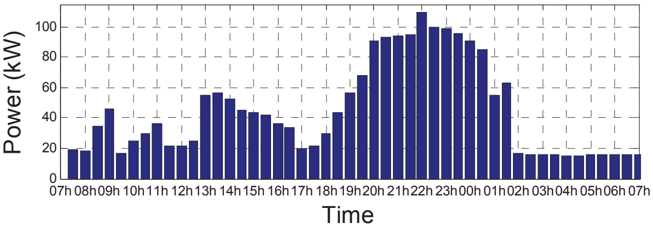

Fig. 7: 24 hour ahead load forecast

The model output is a matrix containing the 24 hour ahead power references for the three generators, the twelve active generator battery state of charges and the amount of micro-gas turbine emissions at each time step (measured in CO_2 equivalent). The algorithm determines the optimal power references planning in regard of the emissions from the three micro gas turbines.

On fig. 8 is presented the obtained sum of all active generator power references. The active generators are located close to each other, thus their embedded PV panels receive about the same solar irradiation. Energy stored in the batteries during the day is discharged at night, as presented on fig.8 in the interval between 19:30 and 20:30. Fig. 9, 10 and 11 show the obtained planning for 30-minute power references for each of the micro-gas turbines.

Using the presented approach, a 19% reduction of CO_2 equivalent is achieved, compared to the same system with setting the gas turbines power references proportional to their rated power output and without optimization.

VII. CONCLUSIONS.

Optimization of the microgrid long term energy management is presented in this paper. The objectives are to maximize the use of the pollution free energy from the PV-based active generator and to minimize the CO_2 equivalent emissions of the three micro gas turbines using a unit commitment by dynamic programming approach. Simulation results demonstrate that this approach is effective and a reduction in the CO_2 equivalent emissions is achieved, compared to the same system without optimization. The presented MCEMS can be used for microgrid control in the context of Smart Grid integration and also for standalone systems.

VIII. REFERENCES:

[1] F. Katiraei, R. Iravani, N. Hatziargyriou, A. Dimeas, "Microgrids management", IEEE Power & energy magazine, p54-65, Vol. 6, No. 3. 4 may/june 2008

[2] S. Stoft, "Power system economics. Designing Market for Electricity", IEEE Press, Piscataway, New Jersey, USA, 2002.

[3] F. Katiarei, M.R. Iravani, "Power management strategies for a microgrid with multiple distributed generation units", IEEE Trans. on Power Systems, vol. 21, No. 4, pp. 1821-1831, November 2006.

[4] B. Awad, J.Wu, N. Jenkins, "Control of distributed generation", Elektrotechnik & Informationstechnik, August 2008

[5] R.E. Brown, "Impact of Smart Grid on Distribution System Design", IEEE Power and Energy Society General Meeting, Pittsburgh, PA, USA, 20-24 July 2008.

[6] N. Prasad Padhy, "Unit commitment-A bibliographical survey", IEEE Transactions on power systems, vol. 19, no.2, 2004

[7] T. Longenthiran, D. Srinivasan, "Formulation of Unit commitment (UC) problems and analysis of available methodologies used for solving the problems", IEEE International Conference on Sustainable Energy Technologies (ICSET), Kandy, Sri Lanka, 6-9 december 2010

[8] Lu, D., François, B., "Strategic framework of an energy management of a microgrid with a photovoltaic-based active generator", Electromotion, EPE, Chapter "Electric drives", joint symposium, Lille, France, 1-3 July 2009, pp. 342-347

[9] N. Hatziargyriou, H. Asano, R. Iravani, C. Marnay, "Microgrids", IEEE Power&Energy magazine, pp78-94, july/august 2007.

[10] B. Kroposki, R.Lasseter, T. Ise, S. Morozumi, S. Papathanasiou, N. Hatziargyriou, "Making microgrids work", IEEE Power&Energy magazine, vol. 6, iss.3, pp.40–53, May-June 2008

[11] M. McGranaghan, A. Chuang, "Functions of a Local Controller to Coordinate Distributed Resources in a Smart Grid", IEEE PES General Meeting, 20-24 July 2008, pp. 1-6

[12] D.Lu, H. Kanchev, F. Colas, V. Lazarov, B. Francois, Energy management and operational planning of a microgrid with a PV-based active generator for Smart Grid Applications, IEEE Transactions on Industrial Electronics, 2011, under publication

[13] H. Kanchev, D. Lu, B. François, V. Lazarov, Smart monitoring of a microgrid including gas turbines and a dispatched PV-based active generator for energy management and emissions reduction, Innovative Smart Grid Technologies Conference Europe (ISGT Europe), IEEE PES, pp. 1-8, Goteborg, Sweden, 11-13 Oct. 2010

[14] A. Canova, G. Chicco, P. Mancarella, " Assessment of the Emissions due to Cogeneration Microturbines under Different Operation Modes", POWERENG 2007, April 12-14, 2007, Setubal, Portugal.

[15] G. Chicco, P. Mancarella, R. Napoli, "Emission assessment of distributed generation in urban areas", Proc. IEEE Power Tech 2007, Lausanne, Switzerland, 1-5 July 2007.

[16] A. Boicea, G. Chicco, P. Mancarella, "Optimal operation of a microturbine cluster with partial-load efficiency and emission caracterisation", IEEE Powertech conference, Bucarest, Romania, june 28th – july 2nd 2009

[17] Climate change connection, "CO2 equivalents", available online: http://www.climatechangeconnection.org/emissions/CO2_equivalents.htm#GWP

[18] International Panel on climate change, "Climate change 2001: Working group I: The scientific basis", Section 4, table 6.7, IPCC 2007.

[19] P. Murty, "Operation and control in power systems", BS Publications, Hyderabad, Pakistan, 2008

[20] T. S. Dillon, G. T. Egan, "Application of Combinational Methods to the Problems of Maintenance Scheduling and Unit Commitment in Large Power Systems," Proceedings of IFAC Symposium on Large Scale Systems Theory and Application, Udine, Italy, 1976

[21] R. Bellman, "A Markovian Decision Process", Indiana Univ. Math. J. 6 No. 4, pp. 679–684, 1957

[22] R. Sioshansi, X. Xi, “A Stochastic Dynamic Programming Model for Co-optimization of Distributed Energy Storage”, submitted for publication in “Management science” review, 2011

[23] V. Puri, “Unit commitment using particle swarm optimization”, master’s degree in power systems and electrical drives thesis, Thapar University, India, 2009

[24] L. Wei, ”Approaches to cost minimization of power systems with distributed generation”, master’s degree in electrical engineering, National University of Singapore, 2003

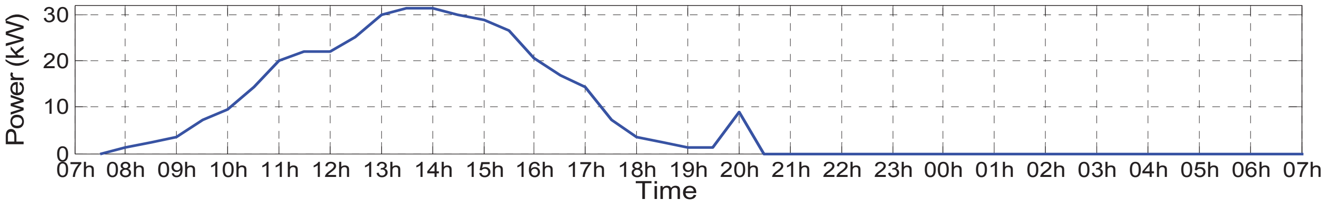

Fig. 8: Power references for the 12 active generators

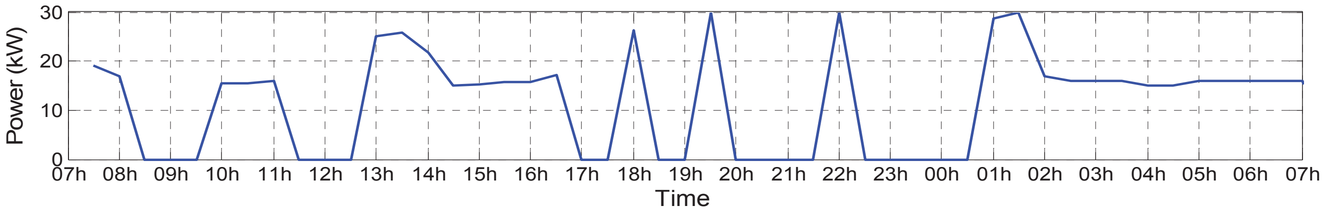

Fig. 9: Power reference for micro gas turbine 1 (30kW rated power)

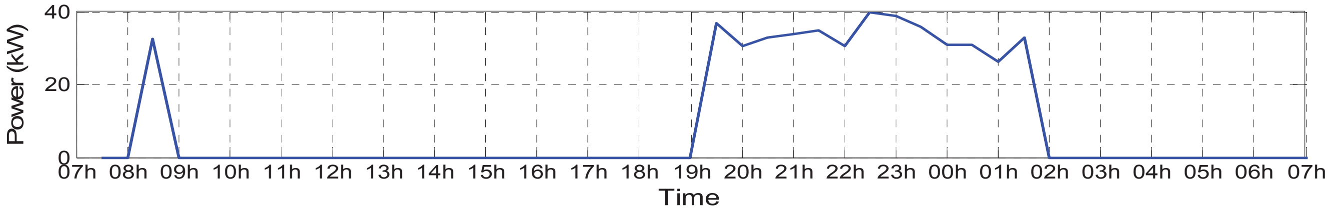

Fig. 10: Power reference for micro gas turbine 2 (40kW rated power)

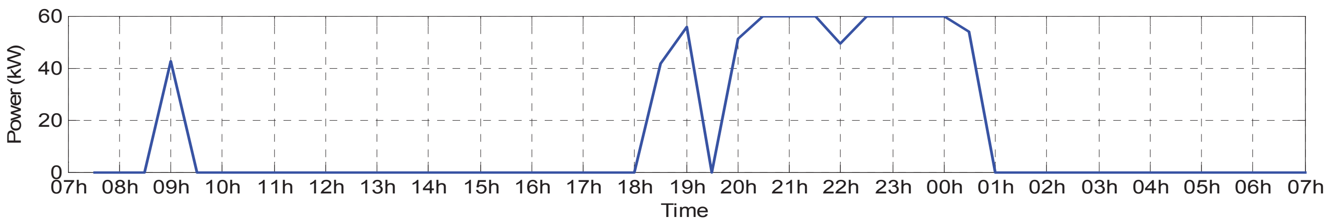

Fig. 11: Power reference for micro gas turbine 3 (60kW rated power)

Hristiyan Kanchev was born in 1984 in Sofia, Bulgaria. He received his master’s degree in electrical engineering in 2008 from the Technical University – Sofia. From 2009 on, he is working towards his PhD degree in electrical engineering at the Technical University-Sofia, Bulgaria and at the Ecole Centrale de Lille, France. His field of interest includes renewable energy sources, distributed electricity generation, energy management and microgrids. Tel. (+359) 889 216547, (+33) 649785362, fax: (+359) 962 4407, (+33) 320335454 , e-mail : hkanchev@tu-sofia.bg, hkanchev@ec-lille.fr

Bruno Francois (M’96-SM’06) received the Ph.D. degree in electrical engineering from the University of Lille, France in 1996. He is Associate Professor at the department of Electrical Engineering of Ecole Centrale de Lille and he is also a member of Laboratory of Electrical Engineering (L2EP), Lille. He has a long experience in the design of control systems for power electronic converters and more exactly multi-phase and multilevel converters. He is currently working on advanced renewable energy based generators and energy management systems for future smart grids. Tel. (+33) 320335459, fax: (+33) 320335454 e-mail: bruno.francois@ec-lille.fr

Vladimir Lazarov was born in Sofia, Bulgaria. He graduated from the Technical University – Sofia, and there he received his PhD. His field of interest includes electrical machines with electronic commutation, small electrical machines, renewable energy sources (electrical aspects). He is today with the Faculty of Electrical Engineering of the Technical University – Sofia and is responsible for the “Laboratory on Renewable Energy Sources”. Tel. (+359) 9652459, fax: (+359) 962 4407, e-mail vl_lazarov@tu-sofia.bg.