Day-ahead optimal and reserve power dispatching in PV based urban microgrid.

Xingyu Y, Abbes D, Bevrani H, Francois B

Published (to be published) in: 18th European Conf on Power Electronics and Applications-EPE'16
ECCE, Karlsruhe, Germany

(Expected) publication date: 2016

Citation format for published version:
Xingyu Y, Abbes D, Bevrani H, Francois B(2016) Day-ahead optimal and reserve power dispatching in PV based urban microgrid. To be presented in 18th European Conf on Power Electronics and Applications-EPE'16 ECCE, Karlsruhe, Germany, 5-9 Sept. 2016.

Day-ahead Optimal Operational and Reserve Power Dispatching in a PV-Based Urban Microgrid

Xingyu YAN, Dhaker ABBES, Bruno FRANCOIS
Univ. Lille, Centrale Lille, Arts et Metiers ParisTech, HEI, EA 2697 -
L2EP - Laboratoire d'Electrotechnique et d'Electronique de Puissance, F-59000 Lille, France
xingyu.yan@ec-lille.fr, dhaker.abbes@hei.fr, bruno.francois@ec-lille.fr

Hassan BEVRANI
Faculty of Engineering, University of Kurdistan
Kurdistan, Sanandaj, PO Box 416, Iran
bevrani@ieee.org

Acknowledgments

The authors would like to thank the government of The Peoples Republic of China (PRC) for its financial support during the research work and EC Lille de Lille (France) for the conference fees.

Keywords

≪Distributed generators≫, ≪Dynamic programming≫, ≪Energy management system≫, ≪Power reserve dispatching≫, ≪Unit commitment problem≫.

Abstract

Accurate sizing of power reserve (PR) due to inaccurate forecast of both renewable energy sources (RES) and load demand in a microgrid can provide substantial cost reductions. This paper proposes two strategies to dispatch the PR into different power generators. The first one uses only micro gas turbine (MGT). The second one uses MGTs plus PV based active generators (AGs). The latter enables the RES to cover the system load demand and PR for some period during a day. To implement those methods, firstly an urban microgrid with PV power generators is introduced. Then, day-ahead optimal planning with dynamic programming (DP) for unit commitment problem (UCP) is applied under several non-linear constraints. Finally, a case study application has been completed to verify the proposed methods.

I. Introduction

RES such as wind and PV power are gradually becoming significant sources of power generations around the word and will considerably reduce the expanded use of fossil fuels. However, energy productions from RES are known as intermittent sources with uncertainty and variability. Thus, in addition to ramping, regulation requirements, and impacts on power system stability, new operation challenges appear for electricity grid operators. Moreover, in many European countries, renewable sources are more and more required to provide ancillary services for grid operators especially if they have to operate in isolated mode [1]. As mentioned in [2], the RES power generation will have impacts on power quality and distribution efficiency in local power systems. Therefore, to maintain a secure operation and grid reliability with a high penetration level of RES, operating PR is required from renewable generators in more and more grid codes [3]. However, with a satisfying security level, this PR should be ideally minimized to keep the system cost down.

Typically, PV power generation forecast is required for system operation as well as for scheduling and dispatching the required PR [4]. Nevertheless, the predicted errors caused by the uncertain nature of RES cannot be eliminated even with the best tools, and the situation is getting worse with load uncertainty. Therefore, accurate PR calculation taking into account the uncertainties from power generation and consumption forecast is essential. In the last few decades, several research projects studied the PR assessment with large amount of RES integration into electricity grid [5, 6, 7]. Moreover, compared with traditional vertically integrated electricity markets where PR is dispatched after completing the energy dispatch, a competitive market must dispatch operational and reserve power simultaneously to maximize the efficiency and reliability of the electrical system [8, 9]. Nonetheless, the previous studies did not take further steps to PR dispatching in RES, especially in microgrid.

Based on the PR quantification results presented in [7], the purpose of this paper is to dispatch it into different power generators in a microgrid with PV AGs. Two different strategies can be considered to distribute the reserve power: the first one separately distributes PR into MGTs before operational energy dispatch, while the other simultaneously allocates the joint operational energy and PR into MGTs and also PV AGs. This second strategy should cover the needed reserve with the same security level but with a smaller battery capacity of AG. The paper is organized as follows: Firstly, the PV AG based microgrid energy management system with a communication system is outlined. Secondly, system uncertainties are analyzed and the method used for PR qualification is briefly introduced. Then day-ahead optimal operational planning is presented and the strategies for power reserve dispatching are detailed. In the final section, case studies with simulation results are presented.

II. Microgrid Energy Management System

II.1. Energy Management System (EMS) with Communication Network

To facilitate the presentation of the theory, a microgrid with PV AG and MGT as power sources is shown in Fig. 1. A central EMS and a local EMS are applied through a communication network. The EMS is used to manage the power and the energy between power sources and loads in the microgrid. The real and reactive power production must be shared among the distributed energy resources and MGTs. The central EMS sends requested power references to the active generator in each operating time period while the local controller distributes them inside the PV AGs. A communication between the two management units is set up for data acquisition and information exchange about the resource states, such as battery capacity and power production [10, 11].

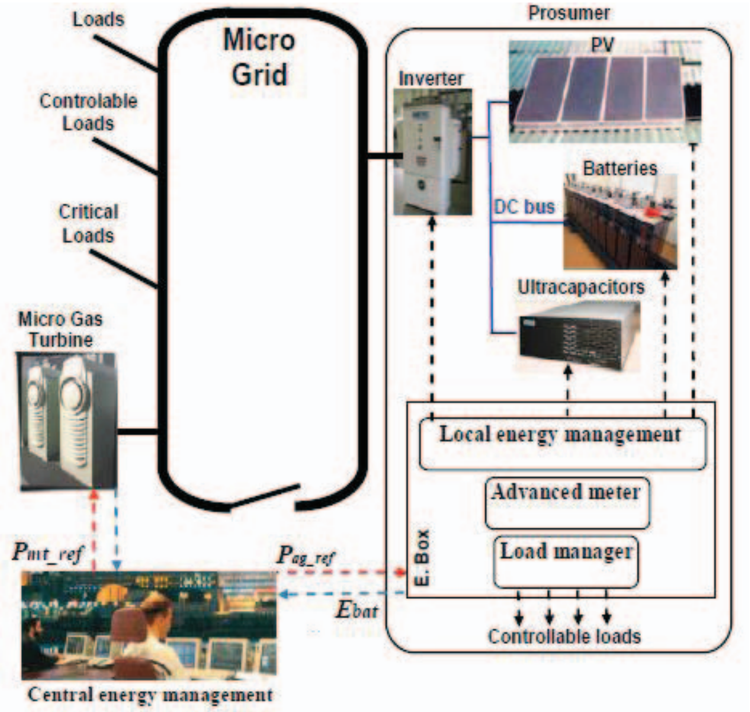

Fig. 1: Microgrid integration of a prosumer and a micro gas turbine.

II.2. PV AG

PV panels associated with a hybrid storage system constitute a PV AG. A set of batteries are implemented as long-term storage device and a set of ultra-capacitors are used for the fast dynamic power compensation. A local EMS is applied for inner instantaneous power balance and power dispatching among the PV power sources and storage units according to the storage capacity and to the specific constraints of each source. Control functions are detailed in [12].

II.3. Micro Gas Turbine

The task is to calculate power reference for the MGT to minimize the pollutant emissions and total fuel cost. Two objective functions can be considered to perform the UCP in section IV. The fuel consumption of MGT can be assessed by using their partial load efficiency features. The equivalent CO_2 emissions are calculated by applying to the various pollutant gases different weights corresponding to their global warming potential. This previous work has been done and can be found with details in [13].

II.4. System Uncertainty Analysis and PR Quantification

Microgrids face major challenges to integrate RES because of intermittent character, low inertia, and limited availability of RES generation units. Data and its analysis are needed to understand the uncertainty and to help operators and planners avoid unnecessary PR. There are many different strategies to manage variability and uncertainty. In general, system operators and planners use mechanisms including forecasting, scheduling, economic dispatch, and reserves to ensure performance that satisfies reliability standards with the minimum cost. The earlier that system operators and planners know what sort of variability and uncertainty they will have to deal with, the more options they will have and the cheaper it will be. The uncertainties of the urban microgrid would come from conventional generators, uncertain load, and power production from RES. As in [7], load demand and PV power generation uncertainties are considered. A probabilistic model has been proposed to calculate the PR based on probability distribution integrating both uncertainties from PV power and load. Moreover, reliability is assessed with the definition of the parameter loss of load probability (LOLP).

III. Operational and PR Dispatching Strategies

In the microgrid presented in Fig. 1, two power sources are considered: PV AG and MGT. The former is preserved as prior source because of its low operating cost and absence of gas emission features, while the latter is set as a backup source for the missing energy. In the first strategy, the PR is only provided by MGTs and at least one of them is set in operation mode. In the second strategy PR is distributed to MGTs and also PV AGs. Therefore, in certain periods all the MGTs will be shut down, and load demand plus PR will be covered only by AGs.

III.1. First strategy: PR provided by MGTs

In this situation, at least one of the MGTs needs to be working at all time to provide the reserve power. Besides the PV power used to cover the load demand, the remaining PV energy will be stored into batteries for night use. The deficit power is provided by MGTs. To cover the load, AG is considered as the prior source and the state of charge (SoC) of battery is calculated firstly. This energy storage can be estimated by the E-box of central EMS. Two cases are distinguished in this situation:

1. If the predicted PV power is more than the predicted load during the time step t ($\tilde{P}_{PV}(t) \geqslant \tilde{P}_L(t)$), then the PV power reference is set to a limited power:

   $$P_{ref\_AG\_n}(t) = \frac{\tilde{P}_L(t)}{N} \tag{1}$$

   N is the total number of available PV AGs. The PR needs to be covered by MGTs. In this situation, if PR is less than the limitation of the minimum MGT power output ($P_R < min(P_{MGT\_m})$), then the MGT must operate at the minimum operating set point and in this situation the reserve will be more than needed. The energy surplus, if it can be absorbed by batteries, is automatically stored by local EMS of PV AG:

$$\sum_{n=1}^{N} E_{Bat\_n}(t+1) = \sum_{n=1}^{N} E_{Bat\_n}(t) + \tau * (\tilde{P}_{PV}(t) - \tilde{P}_L(t)) \tag{2}$$

The parameter τ is the duration of the available constant power.

2. If the predicted PV power is not enough for the predicted load during the time step t ($\tilde{P}_{PV}(t) < \tilde{P}_L(t)$), the PV AGs power references are set as follows:
   - During the day: if PV power is more than 0, the references of PV AGs are set as (3):

     $$P_{ref\_AG\_n}(t) = \frac{\tilde{P}_{PV}(t)}{N} \tag{3}$$

     And MGT must balance remaining load demand and PR:

     $$\sum_{i=1}^{M} P_{ref\_MGT\_n}(t) = \tilde{P}_L(t) - \tilde{P}_{PV}(t) + P_R(t) \tag{4}$$

   - During the night (discharge the battery): If the energy storages are enough to feed the predicted load, then MGTs are used to provide the PR:

     $$\sum_{i=1}^{M} P_{ref\_MGT\_n}(t) = P_R(t) \tag{5}$$

     At each time step, (2) can be used as battery discharge reference with $\tilde{P}_{PV}(t)$ equals to 0. Otherwise, MGTs must balance the remaining load as equation (4) with $\tilde{P}_{PV}(t)$ equals to 0.

III.2. Second strategy: PR provided by both MGT and PV AG

In this case, the reserve and operational power will be distributed into both MGTs and PV AGs. As PV AG is set as the prior energy source, if the PV AG energy (PV power during the daytime and battery energy at nighttime) is more than load and PR, then all the MGTs can be shut down.

1. If the predicted PV power excesses the predicted load demand added with the necessary PR during the time step t ($\tilde{P}_{PV}(t) \geqslant \tilde{P}_L(t) + P_R(t)$), then the power reference is set as limited:

   $$P_{ref\_AG\_n}(t) = \frac{\tilde{P}_L(t) + P_R(t)}{N} \tag{6}$$

   The energy surplus is saved automatically in batteries by the local controller:

   $$\sum_{n=1}^{N} E_{Bat\_n}(t+1) = \sum_{n=1}^{N} E_{Bat\_n}(t) + \tau * (\tilde{P}_{PV}(t) - \tilde{P}_L(t) - P_R(t)) \tag{7}$$

2. If the predicted PV power is not enough for the predicted load and the PR ($\tilde{P}_{PV}(t) < \tilde{P}_L(t) + P_R(t)$):
   - During the day: the PV AG power reference is set to the predicted values, as in equation (3). Then MGTs must balance the remaining load demand, as (4).
   - During the night (discharge the battery): If the energy storage is enough to feed the predicted load and PR, then MGTs are turned off. Otherwise, MGTs must be started to balance the load demand plus the PR, as (4). Battery SoC must be refreshed and checked again at each time step as (7) with $\tilde{P}_{PV}(t)$ equals to 0.

IV. Day-ahead Optimal Operational Planning

As the power industry moves to new restructured forms, the UCP must be adapted to distributed generators including MGTs and RES generators. In this paper the objective function of UCP with dynamic programming is applied to minimize the CO_2 emissions and total fuel cost (Fig. 2). To solve the problem, different operational and reserve power dispatching strategies are performed under several non-linear constraints.

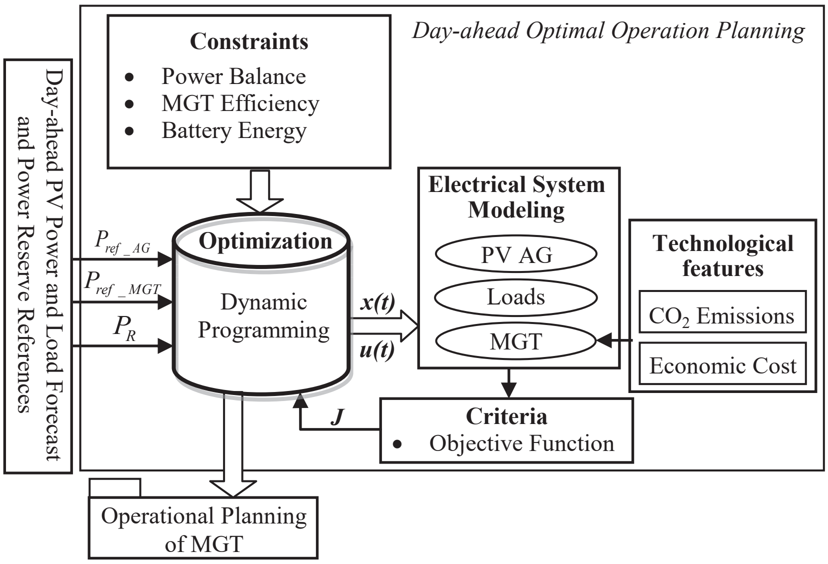

Fig. 2: Day-ahead optimal operational planning scheme.

IV.1. Non-linear Constraints

The general objective is to minimize the total operating cost while satisfying all system constraints. In the presence of N active generators and M micro gas turbines in a microgrid, it is subjected to an equality constraint for PV AG (P_{AG}), MGT generation (P_M), power reserve (P_R) and loads (P_L) balance. Restriction limits of the output related to each unit are as follows:

1. Quantified power reserve ($P_R(t)$) with a security level of x % of LOLP;
2. Power balancing among loads, reserve, and power generation:

$$P_L(t) - P_R(t) - \sum_{n=1}^{N} P_{AG\_n}(t) - \sum_{i=1}^{M} (\delta_i(t) * P_{M\_i}(t)) = 0 \tag{8}$$

3. MGT corresponding inequality constraint:

$$50\% P_{M\_max\_i}(t) \leq P_{M\_i}(t) \leq 100\% P_{M\_max\_i}(t) \tag{9}$$

4. Battery limitations:
    - The batteries SoC have to be kept in a safety range: $SoC_{Max} >$ SoC $> SoC_{Min}$;
    - The charge and discharge power of batteries cannot exceed the power limit $|P_{bat}| < P_{bat\_max}$;
    - If batteries are fully charged, the PV panels must not work in maximum power point.
5. Maximizing the PV energy usage. During the day, the extra PV energy will be stored in batteries as long as the batteries are not full, and then they will be discharged during the night.

IV.2. Formulation of the Unit Commitment Problem (UCP)

The 24-hour ahead operational planning is discretized with T periods. Power references are considered constant during each time period. Actually, they are not, and this is handled by the short-term power balancing functions in the local EMS controller. In our study, power references of MGTs are represented as a vector $x(t)$, and the states of each MGT during each time step are a vector $u(t)$:

$$x(t) = [P_{M\_1}(t), P_{M_2}(t), ..., P_{M_M}(t)] \tag{10}$$

$$u(t) = [\delta_1(t), \delta_2(t), ..., \delta_M(t)] \tag{11}$$

IV.3. Optimization Strategies

For the proposed microgrid energy management, the optimization process tackles to find an output vector $u(t)$ providing the generation set points of MGTs to guarantee the minimum fuel cost or CO_2 equivalent emissions while satisfying the load balance within the settled time interval.

1. Economic criteria: Minimization of the total fuel cost.

The fuel costs ($C_{M\_i}(t)$) are expressed as a non-linear function of its power output. The startup and shutdown penalties increase the emissions and shorten the lifetime of the MGT units. They can be expressed with a CO_2 function as: $C_{P\_C\_i}(\delta_i(t-1),\delta_i(t))$. In this situation, start-up and shutdown penalties are considered equivalent to the consumed fuel cost respectively for 5 minutes and 2.5 minutes at full load. Therefore, the total fuel cost for each MGT can be expressed as:

$$J_{C\_i}(t) = \delta_i(t) * C_{M\_i}(t) + C_{P\_C\_i}(\delta_i(t+1),\delta_i(t)) \tag{12}$$

Then the objective function for the whole system is to minimize the total fuel cost after T operation periods. In this study, if the capital and maintenance costs of PV and MGT generators are taken into consideration, the proposed microgrid energy management objective function can be defined as:

$$J_C(t) = \sum_{t=1}^{T}\sum_{i=1}^{M}(\delta_i(t) * C_{M\_i}(t) + C_{P\_C\_i}(\delta_i(t+1),\delta_i(t))) \tag{13}$$

2. Environmental criteria: Reduction of the CO_2 emissions.

The equivalent CO_2 emissions for each MGT at time step t can be expressed as:

$$J_{CO2\_i}(t) = \delta_i(t) * CO2_{M\_i}(t) + C_{P\_CO2\_i}(\delta_i(t+1),\delta_i(t)) \tag{14}$$

Then the global proposed objective function can be defined as only for CO_2 equivalent emissions:

$$J_{CO2}(t) = \sum_{t=1}^{T}\sum_{i=1}^{M}(\delta_i(t) * CO2_{M\_i}(t) + C_{P\_CO2\_i}(\delta_i(t+1),\delta_i(t))) \tag{15}$$

IV.4. Dynamic Programming (DP) for UCP

In recent decades, the DP principles have been used for the UCP solving in power system planning. UCP with DP algorithm has been described in [14]. DP is a method, which systematically evaluates a large number of possible decisions in a multi-step problem. A subset of possible decisions is associated with each sequential problem step, and a single decision must be made in each step. There is a cost associated with each possible decision, and this cost may be affected by the decision made in the previous step. Additional costs, termed ”transition costs”, may be incurred in going from a decision in one step to a decision in the following step over, called a ”transition path” $(Tr(u(t-1),u(t)))$(Fig. 3).

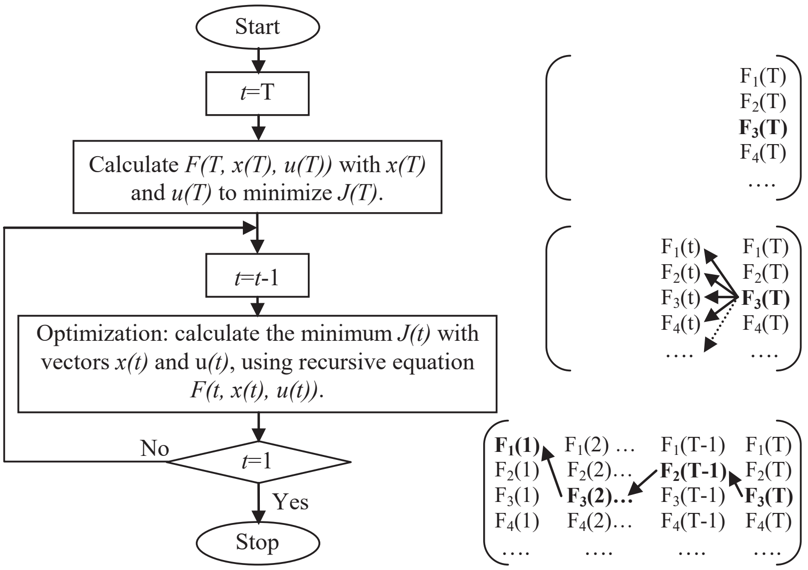

Fig. 3: Dynamic programming algorithm.

The objective is to make decisions in each problem step t to minimize the total fuel cost. For a system with T time steps, if at time step T the minimum running cost is $F(T, x(T), u(T))$, then the total cost of the remaining step $(T-1)$ should be also minimum [15]. In mathematical form $J(T)$:

$$J(t) = F(T, x(T), u(T)) + \sum_{t=1}^{T-1} Tr(F(t), x(t), u(t)) \tag{16}$$

While $Tr(F(t), x(t), u(t))$ is represented as: $F(t, x(t), u(t))$ plus a transition cost ($C_{P\_C\_i}$ or $C_{P\_CO2\_i}$). The objective is to find the vector of the generator states ($u(t)$) and the power references of MGTs ($x(t)$), in (11,12), which minimize the total system cost. The optimal solution of the overall problem is obtained by selecting the optimal $u(t)$ for all time steps recursively from $t = T$ to $t = 1$ as illustrated in Fig. 3.

1. Optimization under economic criteria:

For any one of MGTs state $u(t)$, the operational cost is composed of two parts:

- The total fuel cost during the time step t is: $\sum_{i=1}^{M} \delta_i(t) * C_{M\_i}(t)$
- The cost during the previous time step taking into account the transition cost due to the start-ups or shutdowns of generators is:

$$Tr(u(t-1), u(t)) = F(t-1, u(t-1)) + \sum_{i=1}^{M} C_{P\_C\_i}(\delta_i(t-1), \delta_i(t)) \tag{17}$$

At step t, the UCP formulation for the studied system can be expressed in the form of the following recursive dynamic programming equation:

$$F(t, x(t), u(t)) = \sum_{i=1}^{M} \delta_i(t) * C_{M\_i}(t) + Tr(u(t-1), u(t)) \tag{18}$$

2. Optimization under environmental criteria:

A similar formulation is found to evaluate CO_2 emissions:

$$F(t, x(t), u(t)) = \sum_{i=1}^{M} \delta_i(t) * CO2_{M\_i}(t) + Tr(u(t-1), u(t)) \tag{19}$$

$$Tr(u(t-1), u(t)) = F(t-1, u(t-1)) + \sum_{i=1}^{M} C_{P\_CO2\_i}(\delta_i(t-1), \delta_i(t)) \tag{20}$$

V. Optimal Reserve Power Dispatching Application for UCP with DP

In this case study, a system with 110 kW of rated load, 55 kW of rated PV power, three MGTs with rated power respectively 30, 30, 60 kW, and the PR, which comes from the uncertainty assessment with 1%

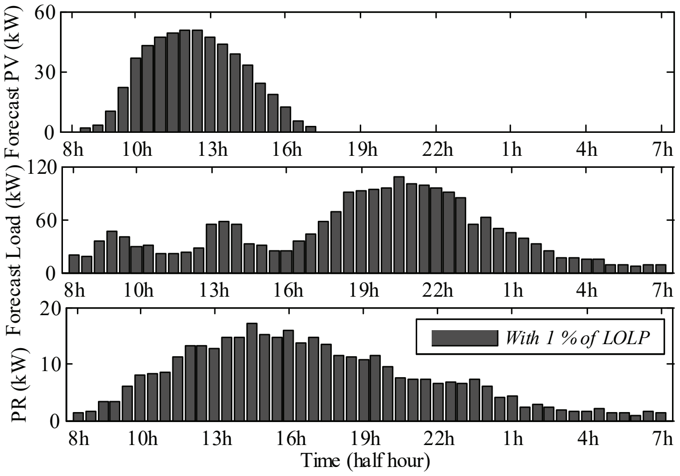

Fig. 4: Day-ahead PV power forecast, load forecast and power reserve with 1 % of LOLP.

of LOLP, has been taken into consideration (Fig. 4). The 24-hour ahead optimal operational planning is discretized with 48 periods ($T = 48$) for each 30 minutes ($\tau = 0.5$). With the power planning algorithm presented above, the simulation results are displayed and discussed below.

V.1. Different Scenarios of DP Application

The DP based optimization procedure has been performed with two objective functions, which are CO_2 equivalent emission minimization and total fuel cost minimization. Three different scenarios have been taken into consideration:

- Scenario 1: Without PV power generation: PV power production equals to 0 (for example totally cloudy days), and all the load demand and PR are covered by MGT.
- Scenario 2: With PV power, PR provided by MGT (**First strategy**).
- Scenario 3: With PV power, PR provided by both PV AGs and MGT (**Second strategy**).

Compared with scenario 1, the results in Table I show that total cost and pollution in scenarios 2 and 3 are reduced about 18% and 15% respectively (thanks to the PV power usage). In addition, within each scenario, the system cost and pollution are lower with optimization. In scenario 2, there is no PR dispatched in PV AGs, but a bigger battery is needed compared to the situation in scenario 3, which has 38.9% of PR provided by AG.

Table I: Day-ahead Operational Planning Results

Scenario	Optimize strategy	Cost (€)	Pollution (kg)	PR on AG (%)	$E_{battery\_Max}$(kWh)
1	None	219	1392	0	0
	Environmental	212	1196	0	0
	Economic	210	1263	0	0
2	None	183	1156	0	80.2
	Environmental	181	1067	0	80.2
	Economic	178	1120	0	80.2
3	None	182	1098	38.9	54.1
	Environmental	179	991	38.9	54.1
	Economic	177	1061	38.9	54.1

V.2. Comparison of PR Dispatching

Fig. 5 demonstrates the PR dispatching among different power generators with scenario 2 and 3, respectively. To simplify the explanation, the results are chosen with the economic strategy (and so are the figures below). As can be seen in Fig. 5(b), from 11h to 13h and from 4h to 7h (next day) the PR is provided only by AG, as well as in some other time steps, it is covered by both MGT and AG. Instead, in Fig. 5(a), the entire PR comes from MGTs only.

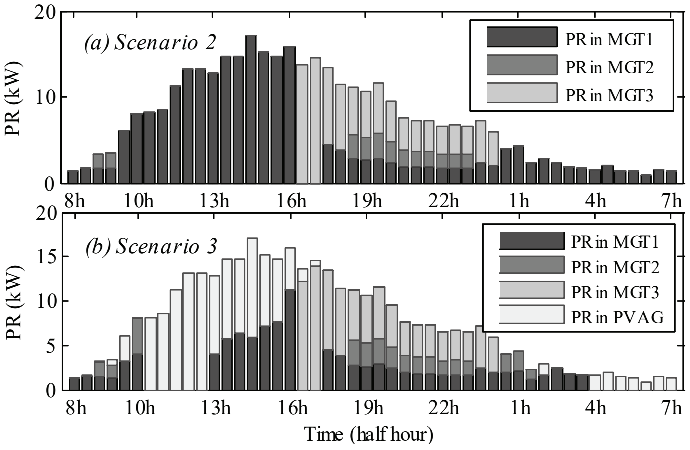

Fig. 5: Power reserve dispatching in scenario 2 and 3.

V.3. Characteristics of PV AG (in scenario 3)

Fig. 6 gives an example of reference power of PV AG, charge/discharge and SoC of battery. As can be seen, PV AG provides the power both during daytime and nighttime. In the daytime, the energy comes from PV panels while during the night it comes from the discharge of the battery. The maximum charge power is 18 kW and discharge power is about 15 kW. The maximum storage is 54.1 kWh, which is much smaller than 80.2 kWh in scenario 2 (in Table I). The reason is that in scenario 2 much more PV energy needs to be stored into the batteries during the day.

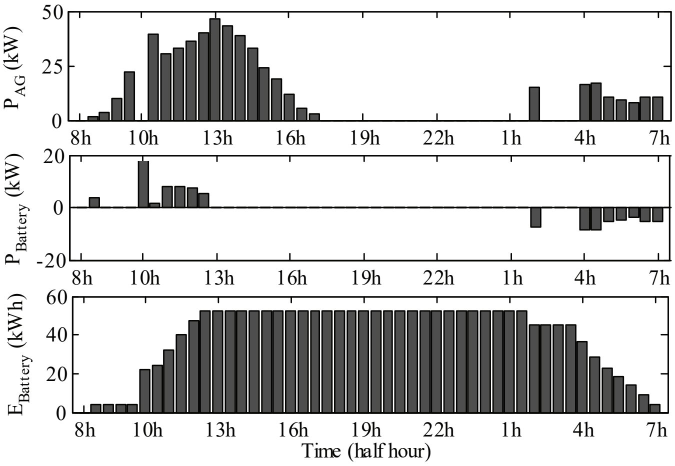

Fig. 6: Reference power of AG, battery power and energy.

V.4. Security Level Analysis

Fig. 4 indicates that the PR is calculated with 1% of LOLP. However, after operational and reserve power dispatching, the MGTs usually cannot reach their maximum output. Therefore, with those remaining power plus original PR, a novel LOLP can be calculated. The novel results are presented in Fig. 7. It is clear that scenario 2 has a great improvement on security level as LOLP, which decreases from 1 % to almost below 0.1% at each step. While in scenario 3, some improvement appears excepted during the steps when all the power is coming from batteries. It represents the risk that electrical systems need to face in this situation.

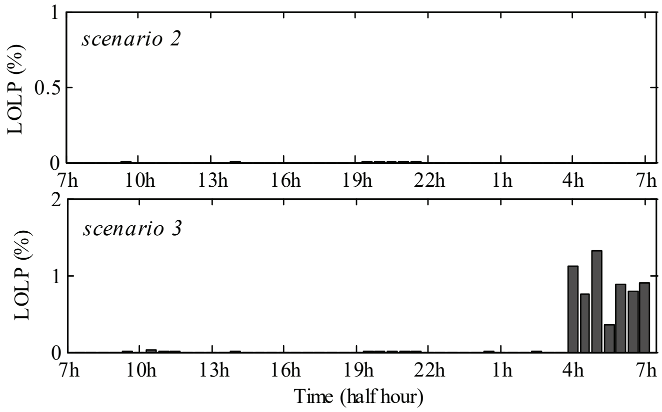

Fig. 7: LOLP for each half-hour with the scenario 2 and 3.

VI. Conclusion

RES power productions are intermittent with low inertia. Their integration in the electricity grid with good reliability is still an important issue. It is essential to obtain an appropriate PR with an acceptable risk level. However, a good way for PR dispatching is also needed. In this paper, a day-ahead optimal operational planning has been applied to calculate power references with two different dispatching strategies of operational and reserve power. A DP approach has been used for the UCP solving in order to minimize equivalent CO_2 emissions and the total fuel cost. From the established results that have been carried out, it is possible to conclude that PV AG can contribute better in reserve power dispatching without losing the security of the system. The results also show that total fuel cost and pollution are reduced by adding PV power generation in the system. The future research field will be concentrated on increasing the RES (PV power) penetration rate with a reasonable battery size to minimize total fuel cost and CO_2 emissions of the system.

References

[1] E. Romero-Cadaval, B. Francois, M. Malinowski, and Q.-C. Zhong, ”Grid-Connected Photovoltaic Plants: An Alternative Energy Source, Replacing Conventional Sources,” Industrial Electronics Magazine, IEEE, vol. 9, pp. 18-32, 2015.

[2] L. E. Jones, Renewable energy integration: practical management of variability, uncertainty, and flexibility in power grids: Academic Press, 2014.

[3] A. Ipakchi and F. Albuyeh, ”Grid of the future,” Power and Energy Magazine, IEEE, vol. 7, pp. 52-62, 2009.

[4] A. Mills, ”Integrating Solar PV in Utility System Operations,” Argonne National Laboratory, LBNL-6525E, Mar, 2014.

[5] M. A. Matos and R. J. Bessa, ”Setting the operating reserve using probabilistic wind power forecasts,” Power Systems, IEEE Transactions on, vol. 26, pp. 594-603, 2011.

[6] M. A. Ortega-Vazquez and D. S. Kirschen, ”Estimating the spinning reserve requirements in systems with significant wind power generation penetration,” Power Systems, IEEE Transactions on, vol. 24, pp. 114-124, 2009.

[7] X. Yan, B. Francois, and D. Abbes, ”Operating power reserve quantification through PV generation uncertainty analysis of a microgrid,” in PowerTech, 2015 IEEE Eindhoven, 2015, pp. 1-6.

[8] A. Shrivastava, A. Bhatt, M. Pandit, and H. M. Dubey, ”Dynamic Energy and Reserve Dispatch Solutions for Electricity Market with Practical Constraints: Intelligent Computing Technique,” in Communication Systems and Network Technologies (CSNT), 2014 Fourth International Conference on, 2014, pp. 990-994.

[9] A. Bhatt, A. Shrivastava, M. Pandit, and H. Mohan Dubey, ”Dynamic scheduling of operating energy and reserve in electricity market with ramp rate constraints,” in Recent Advances and Innovations in Engineering (ICRAIE), 2014, 2014, pp. 1-6.

[10] H. Kanchev, D. Lu, F. Colas, V. Lazarov, and B. Francois, ”Energy management and operational planning of a microgrid with a PV-based active generator for smart grid applications,” Industrial Electronics, IEEE Transactions on, vol. 58, pp. 4583-4592, 2011.

[11] D. Lu and B. Francois, ”Strategic framework of an energy management of a microgrid with a photovoltaic based active generator,” in Advanced Electromechanical Motion Systems & Electric Drives Joint Symposium, 2009. ELECTROMOTION 2009. 8th International Symposium on, 2009, pp. 1-6.

[12] D. Lu, T. Zhou, H. Fakham, and B. Francois, ”Design of a power management system for an active PV station including various storage technologies,” in Power Electronics and Motion Control Conference, 2008. EPE-PEMC 2008. 13th, 2008, pp. 2142-2149.

[13] H. Kanchev, F. Colas, V. Lazarov, and B. Francois, ”Emission Reduction and Economical Optimization of an Urban Microgrid Operation Including Dispatched PV-Based Active Generators,” IEEE Transactions on Sustainable Energy, 2014.

[14] W. L. Snyder, H. D. Powell, and J. C. Rayburn, ”Dynamic programming approach to unit commitment,” Power Systems, IEEE Transactions on, vol. 2, pp. 339-348, 1987.

[15] N. P. Padhy, ”Unit commitment-a bibliographical survey,” Power Systems, IEEE Transactions on, vol. 19, pp. 1196-1205, 2004.