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PHOTOVOLTAIC PRODUCTION MANAGEMENT IN STOCHASTIC OPTIMIZED MICROGRIDS

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The microgrids are composed of small scale fueled generation capacities, renewable energy sources, storage energy systems, controllable loads, and autonomously can connect or disconnect from the mains supply. The microgrids can operate connected to the upstream main grid, or in an islanded operation mode following a large perturbation in the upstream grid. The microgrid analyzed in this paper is composed of a photovoltaic system, a thermal engine, an electrochemical storage system, critical and interruptible loads. As backup generation is considered a classical generation engine and a small scale storage unit. The autonomous switching between grid-connected and islanding operation modes can occur, under an excess/deficit of generation and function of the electricity market price. The paper deals with an optimization model for minimizing the microgrid operation costs under intermittent generation and variable demand function of microgrid operation constrains. The optimization model is tested on a 24 hours horizon. The grid-connected optimized operation accounts also the exchanged power with the upstream grid function of the electricity price within the public network.

Keywords: Microgrids, Photovoltaic system, Renewable sources integration, Demand-response, Optimization model

1. Introduction

The development of generation, transport, distribution, and consumption of electrical energy determined the shifting from a bulk power supply structure to the microgrid supply system, in urban and newly developing areas, as well as where is possible to efficiently use renewable sources delivering electrical energy to local customers at lower prices compared to mains supply. The microgrid contains distributed energy resources (DERs) and local loads, and can automatically connect

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or disconnect from the upstream grid, also function of the electricity price within the microgrid compared with the one from the upstream grid [1-3]. This new concept demands for a high flexibility of sources (mainly small scale renewable energy sources) and end-users, achieved thanks to the development of power electronic interfaces rapidly answering to the intermittency of new energy sources and to the load changing.

The microgrids require finding specific systems for storing energy, and control systems to optimally dispatch the available power between sources and loads [4-9]. In [4], a smart energy management system was proposed to optimally coordinate the power production of distributed generators and storage systems such that to minimize operational costs. Within distribution microgrids, the stochastic renewable energy sources (RES) like photovoltaic (PV) systems and storage devices are optimally dispatched for reducing the operation costs and preserving storage utilization, considering the electrical energy price of selling/purchasing energy and supplying the load [5]. Ref. [6] proposes an intelligent energy management system for cost minimization of microgrid operation, forecasting renewables with artificial intelligence based modules and scheduling the storage systems to balance microgrid uncertainties. Ref. [7] proposes an optimization model to reduce cost of energy, improve service continuity, reduce power fluctuations determined by volatile sources, reduce peak loading and emissions. The microgrid operation for minimizing costs under its participation on electricity market is investigated in [8], but not considering the 24 hours pattern of demand and electricity price. The hierarchical control analysis and detail of its 3 layers are conducted in [9], considering the grid-connected an islanding operation modes, mainly focusing on the control system of power electronic devices from the microgrid. The optimized operation of the microgrid must also consider the availability of local generation and storage state of charge such that to ensure security of supply to local critical load in case of islanding occurrence [10].

The optimized operation of microgrids in presence of electric vehicles and responding loads is investigated in [11], where the vehicles are sued for peak shaving and responding loads provide the reserve to cover renewable energy sources uncertainties. The demand response utilization in microgrid operation is investigated in [12], highlighting the possibility to reduce the overall costs by shifting electricity demand from peak periods to off-peak periods.

Stochastic energy management models have been proposed to cope with the uncertainty in generation/consumption and the impact on microgrid operation [13-16]. Ref. [13] proposes a stochastic model to face the uncertainties of renewable energy sources production, while [14] investigates the stochastic charging management of electric vehicles. Ref. [15] investigates microgrid reliability and storage systems scheduling using stochastic methods. A stochastic based framework to model the uncertainty associated with load forecast error, photovoltaic and wind power generation intermittency, and the market prices is proposed in [16].

The microgrids can disconnect, in case of faults, from the upstream grid to supply the islanded demand and the critical loads [17]. The islanding operation can occur during periods with excessive load and insufficient generation, and load curtailment controls must be applied to maintain the secure operation of microgrid [18]. A compromise must be made between operational costs and load curtailment occurring in case of uncertain islanding operation.

This paper proposes an optimized scheduling of microgrid grid-connected and in islanding operations for a 24 hour time horizon, with 15 minutes time slots, minimizing costs considering generation and demand operational constraints. The 15 minutes analysis allows to investigate the microgrid operation under sudden changes in renewable energy sources production, i.e. shadowing occurrence of photovoltaic installation within the microgrid. Two case studies are considered: I) minimizing microgrid operating costs under perfectly known photovoltaic production, and II) stochastic optimization model under intermittent photovoltaic production. The case studies I and II are investigated under *hypothesis A* (grid-connected operation), respectively *hypothesis B* (islanding occurrence).

The remainder of the paper is organized as follows. In section 2, the analyzed microgrid structure is introduced and described. The two objective functions of the mathematical models are presented in section 3. In section 4, the proposed microgrid scheme is analyzed under perfectly known and uncertain photovoltaic production. The concluding remarks are discussed in section 5.

2. Structure of analyzed microgrid

The microgrid investigated in the paper has local generation units (like more precisely photovoltaic units and fueled thermal engines), battery energy storage systems, critical and interruptible loads. The microgrid is schematically illustrated in Fig. 1. The microgrid controller can acquire or sell energy with the mains supply. The load is divided into non-dispatchable load, i.e. critical load, and interruptible load. Function of operating conditions and availability of local resources, a share of total interruptible load can be disconnected. During grid connection operation, it is hypothesized that the upstream grid can supply the entire load and there are no interconnection limiting constraints between the microgrid and the upstream grid, thus no load curtailment should occur during grid-connected mode of operation. During islanding operation, as load interruption has social impact and is costing in accordance, the load curtailment should be as low as possible.

As local generators are considered photovoltaic units and thermal engines. The photovoltaic systems are more suited to microgrids within local distribution grids from urban areas. Their increased diffusion in urban areas determined the necessity to face their production intermittency and in-time decay of their energy production. The production of these sources is uncertain and forecasting methods are applied to better estimate their production. The recorded power production curve for a 300 kW photovoltaic plant (PV) is illustrated in Fig. 2, for a summer day.

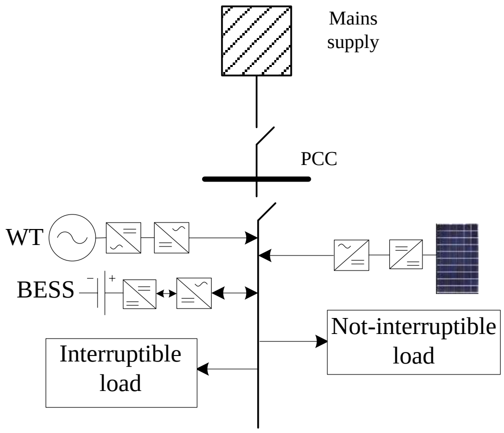

Fig. 1. Schematic structure of the considered microgrid

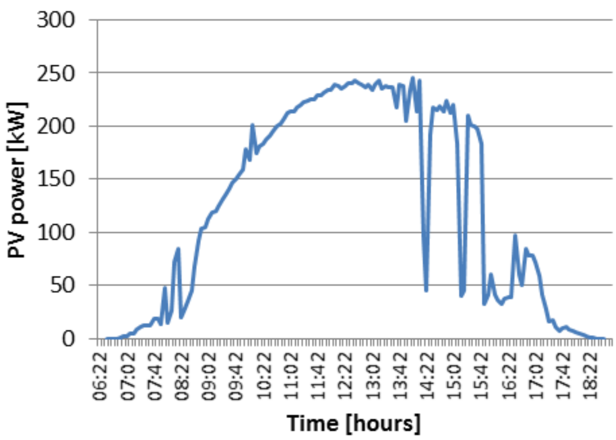

Fig. 2. Recorded production curve of PV system.

In Fig. 2, as it can clearly observed, the curve accounts for the clouding periods when the PV production is reduced. In the present paper, only PV systems are considered as renewable source. Other types of renewable energy sources, like wind turbines can be considered if their production is known or can be accurately forecasted.

A classical back-up source is used within the scheme as a dispatchable unit [19]. The cost function C_g of this classical unit (CU) is a quadratic function of the amount of energy $E_{CU}(t)$, at each time period t, with a cost function expressed as:

$$C_g\left(E_{CU,g}(t)\right)=a_g\cdot E_{CU,g}^2(t)+b_g\cdot E_{CU,g}(t)+c_g\ ,\forall g\in S_{CU},\ \forall t \tag{1}$$

where a_g, b_g, and c_g are the cost function coefficients for each unit within the set of classical units S_{CU}, expressed in Euro/MWh.

The output power state of the classical unit is modeled with the help of a binary variable $u_g(t)$ (equal with 0 if the unit is off, and 1 if the unit is on):

$$u_g(t)\cdot P_{CU,g}^{\min}\le P_{CU,g}(t)\le u_g(t)\cdot P_{CU,g}^{\max}\ ,\forall g\in S_{CU},\ \forall t \tag{2}$$

where $P_{CU,g}^{min}(t)$ and $P_{CU,g}^{max}(t)$ are the minimum and maximum output powers of the classical unit g.

The startup cost C_g^{SU} and shutdown cost C_g^{SD} associated with the classical fueled unit are expressed with the constraints (3a) and (3b):

$$C_g^{SU}(t)\ge S_g^U\cdot\left(u_g(t)-u_g(t-\tau)\right),\forall g\in S_{CU},\ \forall t$$
$$C_g^{SU}(t)\ge 0,\forall g\in S_{CU}\ ,\ \forall t \tag{3a}$$

$$C_g^{SD}(t)\ge S_g^D\cdot\left(u_g(t-\tau)-u_g(t)\right),\forall g\in S_{CU},\ \forall t$$
$$C_g^{SD}(t)\ge 0,\forall g\in S_{CU}\ ,\ \forall t \tag{3b}$$

where S_g^U and S_g^D are the actual costs of turn on/off of the classical unit.

The storage battery energy systems are increasingly deployed in the existing distribution networks. Their flexibility and potential to smooth the output power of renewable energy sources determined the widespread within the distribution networks. The state-transition equation for the energy level $E_{st,i}(t)$ with finite capacity, for each storage unit i from the set of storage units S_{st} at any time t, is:

$$E_{st,i}(t)=E_{st,i}(t-\tau)+P_{st,i}^{chg}(t)\cdot\eta_i\cdot\tau-\frac{P_{st,i}^{dischg}(t)}{\eta_i}\cdot\tau \tag{4}$$
$$E_{st,i}^{\min}\le E_{st,i}(t)\le E_{st,i}^{\max}\ ,\forall i\in S_{st},\ \forall t$$

where τ represents the time frame, and η_i are the conversion efficiencies that accounts for the energy losses associated with the charging and discharging processes, and are lower than 1. $P_{st,i}^{chg}(t)$ and $P_{st,i}^{dischg}(t)$ are, respectively, the charging and discharging powers of each storage unit i, limited by certain upper bounds (i.e. $P_{st,i}^{chg,max}$, respectively $P_{st,i}^{dischg,max}$) expressed as:

$$0\le P_{st,i}^{chg}(t)\le P_{st,i}^{chg,\max}\ ,\forall i\in S_{st},\ \forall t \tag{5a}$$

$$0\le P_{st,i}^{dischg}(t)\le P_{st,i}^{dischg,\max}\ ,\forall i\in S_{st},\ \forall t \tag{5b}$$

It is considered that there is no transfer constraint between the upstream grid and the microgrid. Thus, during grid-connected operation no load curtailment should occur. If this is not the case, a constraint should be added to limit the power flow. For minimizing the microgrid operating costs, it is considered that the interruptible load can be reduced during periods with high electricity prices in the upstream grid or when the microgrid is in islanding operation state. The load curtailment has a high penalty cost for the microgrid. The power demand $P_{crit\_l,j}(t)$ of the critical load j from the set of critical loads S_{crit_l} is constrained to be:

$$P_{crit\_l,\,j}^{\min} \le P_{crit\_l,\,j}(t) \le P_{crit\_l,\,j}^{\max}\,,\ \forall j \in S_{crit\_l},\ \forall t \tag{6}$$

while the power demand $P_{inter\_l,k}(t)$ of the interruptible load k from the set of interruptible loads S_{inter_l} is bounded by:

$$0 \le P_{inter\_l,\,k}(t) \le P_{inter\_l,\,k}^{\max}\,,\ \forall k \in S_{inter\_l},\ \forall t \tag{7}$$

3. Energy management model

The supervisory control system enables the supply of loads with minimum operating costs in presence of photovoltaic systems, classical units and storage devices. This can be achieved by using the internal resources as much as possible and determining the amount of transfer with the upstream grid at various time periods function of different electricity market prices and photovoltaic production forecasts. Thus, it is obvious that the optimization model determines the utilization of local generation whenever the electricity price is very high, and commands the storage charging whenever the price is low.

In case of upstream fault occurrence, the microgrid will be separated from the upstream grid and will start operating in islanding operation mode [20]. The local loads will be supplied using the available resources, with the condition that these are completely available. Thus, the supervisory controller ensures the optimal security and equilibrium of the production-consumption when the microgrid is in islanding operation mode.

This paper proposes an efficient method for optimally operating microgrids by minimizing the functioning costs, under grid-connected and islanding modes, accounting for intermittent production of photovoltaic systems and critical load supply. The battery energy storage should be used such that to preserve its lifetime, reducing the number of charging/discharging cycles.

3.1. Perfectly known photovoltaic production

In this case, the forecasted photovoltaic production is considered perfectly accurate. The optimization model for minimizing the operation costs (Cost) during the 24 hours operation mode can be formulated as:

$$[\text{MIN}]\,\text{Cost} = \sum_{t}^{T} \left[\begin{array}{l} \sum_{i \in S_{ThE}} \left[C_g\left(E_{CU,g}(t)\right) + C_g^{SU}(t) + C_g^{SD}(t) \right] + \\ \sum_{s \in S_{RES}} \pi_{PV,s}(t) \times P_{PV,s}^{curt}(t) \times \tau \\ + \sum_{j \in S_{crit\_l}} \pi_{crit\_l,j}(t) \times E_{crit\_l,j}(t) - \pi_{el}(t) \times P_{exch}(t) \times \tau \end{array} \right] \tag{8}$$

where π_{PV} is the penalty cost associated with the PV curtailed power $P_{PV,s}^{curt}$, π_{crit_l} is value of lost load P_{crit_l}, π_{el} is the electricity market price, and $P_{exch}(t)$ is the amount of power exchanged with the upstream grid in time period t. The power exchange is positive when the power is flowing towards the mains supply, or negative if the power is going towards the microgrid.

The energy balance constraint ensures, for each time frame τ, that the sum of total generated energy (the energy generated by the classical unit, the forecasted value of the PV unit, and the storage system discharge) is equal to the total load (energy consumed by the loads and for charging the storage system), plus the energy exchanged with the upstream grid:

$$\begin{aligned} &\sum_{g \in S_{CU}} E_{CU,g}(\tau) + \left(\sum_{s \in S_{RES}} P_{PV,s}^{fcast}(t) - \sum_{s \in S_{RES}} P_{PV,s}^{curt}(t) + \sum_{i \in S_{st}} P_{st,i}^{dischg}(t) \right) \cdot \tau = \\ &= \sum_{j \in S_{crit\_l}} E_{crit\_l,j}(\tau) + \sum_{k \in S_{inter\_l}} E_{inter\_l,k}(\tau) + \left(\sum_{i \in S_{st}} P_{st,i}^{chg}(t) + P_{exch}(t) \right) \cdot \tau \end{aligned} \tag{9}$$

The forecasted PV production value $P_{PV,i}^{fcast}(t)$ is accurately known, while the outputs at each time moment t are the variables $E_{CU,g}(t)$, $E_{crit\_l,j}(t)$, $E_{inter\_l,k}(t)$, $P_{PV,s}^{cut}(t)$ $P_{st,i}^{dischg}(t)$, $P_{st,i}^{chg}(t)$, $E_{st,i}(t)$ and $P_{exch}(t)$.

3.2. Stochastic scheduling model

During microgrid operation, the forecasted values of PV production in practice cannot be accurately predicted. The magnitude of errors depends on the accuracy of the forecast programs [21, 22]. Hence, the microgrid energy balance cannot be fulfilled under different PV productions, which can occur when the load demand is very low or during islanding operation mode. This islanding duration is unknown and the microgrid should have the resources to supply the local loads. For overcoming this possibility, an optimization models is formulated considering the uncertainties in PV production. For each uncertainty of PV production, a certain probability of occurrence λ is assigned, i.e. λ ≥ 0 and the sum of probabilities for all set of scenarios n_{sc} is $\sum_{r=1}^{n_{sc}} \lambda_r = 1$. The stochastic optimization model minimizing the operation costs can be formulated as:

$$\begin{aligned}[\mathrm{MIN}]\,Cost = \sum_{t=1}^{24} \Big[& -\pi_{el}(t)\times P_{exch}(t)\times 1 + \\ & +\sum_{r=1}^{n_{sc}} \lambda_r \cdot \Big[\sum_{g\in S_{CU}} \Big[C_g\big(E_{CU,g,r}(t)\big) + C_{g,r}^{SU}(t) + C_{g,r}^{SD}(t)\Big] + \\ & + \sum_{s\in S_{RES}} \pi_{PV\_curt,s,r}(t)\times P_{PV\_curt,s,r}(t)\times\tau + \\ & + \sum_{j\in S_{crit\_l}} \pi_{crit\_l,j}(t)\times E_{crit\_l,j,r}(t)\Big]\Big]\end{aligned} \tag{10}$$

for each scenario *r* from the set of all considered scenarios.

The energy balance constraint (11) ensures that, for each time period *t* and for each PV production scenario *r*, the sum of total generated energy by classical unit, photovoltaic scenario production and battery discharge equals the sum of load demand, battery charging and exchanged energy with the upstream grid.

$$\begin{aligned}&\sum_{g\in S_{CU}} E_{CU,g,r}(\tau) + \left(\sum_{s\in S_{RES}} P_{PV,s,r}^{stoch}(t) - \sum_{s\in S_{RES}} P_{PV,s,r}^{curt}(t) + \sum_{i\in S_{BESS}} P_{BESS,i,r}^{dischg}(t) \right)\cdot\tau = \\ &= \sum_{j\in S_{crit\_l}} E_{crit\_l,j,r}(\tau) + \sum_{k\in Sinter\_l} E_{inter\_l,k,r}(\tau) + \left(\sum_{i\in S_{BESS}} P_{BESS,i,r}^{chg}(t) + P_{exch}(t) \right)\cdot\tau\end{aligned} \tag{11}$$

In the grid-connected mode, the power exchanged with the mains supply is established prior to knowing the real output of PV production, and thus is independent of the scenarios realization. For each PV production scenario, the variables of the optimization model are determined.

4. Simulation results

The capacities and important characteristic data of all units within the simulated microgrid illustrated in Fig. 1 are reported in Table 1. The operation costs of renewable energy sources and battery storage are considered to be negligible in the case studies. The thermal engines are supplied with gas, with fast turn on/off capabilities. The load demand is composed of the critical load 60%, and the interruptible load 40%. Critical load curtailment costs are set to 50 Euro/kWh. The electrical energy prices represent an important parameter that can greatly influence the optimized operation of the microgrid. The electricity prices are typical average values on the day-ahead market, on a 24 hour interval.

Table 1

Characteristic data of units

Component	Value
Photovoltaic plant	300 kW
Battery energy storage system	200 kW
- minimum storage level	40 kW
- conversion efficiency	0.9
Engine capacity	600 kW
- engine cost function coefficients {a; b; c}	{0.03; 1; 1.3}
Maximum demand	800 kW

Each of the energy management models presented in section 3 are tested in three cases defined as:

Case I: optimal energy scheduling for minimizing microgrid operation costs under perfectly known photovoltaic production;

Case II: optimal energy scheduling for minimizing microgrid operation costs under uncertainty of photovoltaic production.

Case I. The photovoltaic production is perfectly known, and is given by the forecasted production values illustrated in Fig. 2. The optimal energy scheduling for minimizing the operation cost must consider the existing connection between the microgrid and the upstream grid. In this paper, there is no constraint of transfer capacity between the microgrid and the upstream grid.

Hypothesis A. The microgrid is operating during the 24 hours analysis horizon interconnected with the upstream grid. The results of the optimization model related to thermal engine operation and battery discharge, as well as the model input PV production, are illustrated in Fig. 3. The optimization model results related to consumption schedule within the microgrid are illustrated in Fig. 4. The electricity price follows the daily typical curve. During periods when the electricity price is low, i.e. during the night, the microgrid is purchasing energy from the upstream grid to supply the load. In addition, the storage energy system is charged in this period. In the time interval t = 20–34 (i.e. from hour 05:00 to hour 08:30) the electricity market price and the load are increasing. In this period, is more economical to purchase the required electrical energy from the upstream grid instead of locally generating with the thermal engine. In Fig. 4, from time instant t = 34 (i.e. from hour 08:30) the photovoltaic installation starts producing the required power to balance the demand. During midday, when the electricity price is high, the excess of local PV resources production is injected into the upstream grid, and no constraint is imposed to renewable sources connected to the network. After the 20th hour, the electricity price and demand are high and the PV production is zero. The thermal engine is switched on and the battery is discharged to supply the microgrid demand.

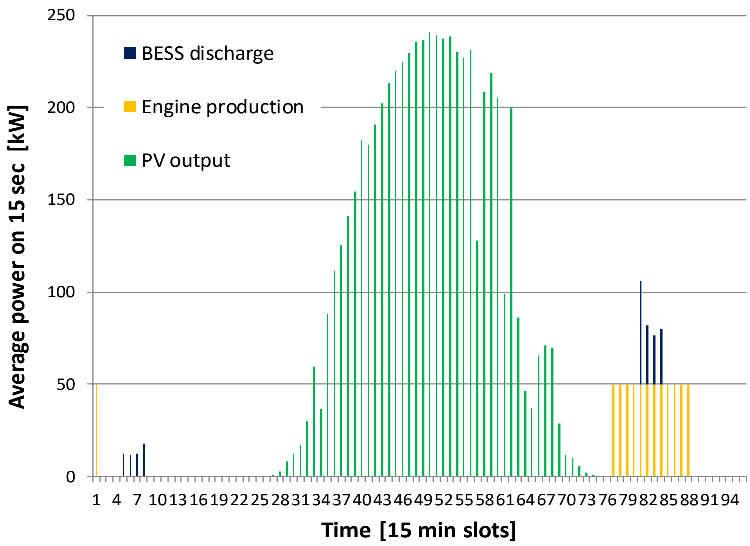

Fig. 3. Resulting generation schedule within the microgrid, *case I*, *hypothesis A*

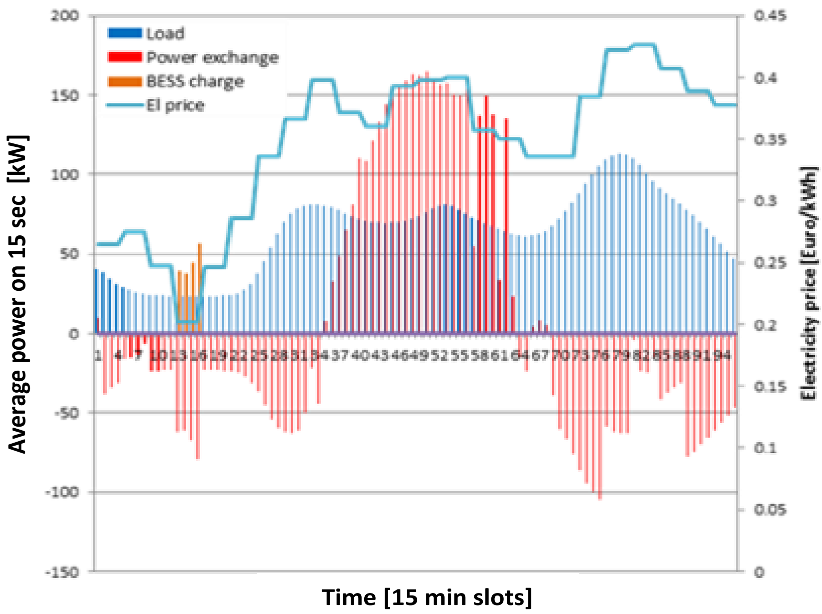

Fig. 4. Resulting consumption schedule within the microgrid, *case I*, *hypothesis A*

Hypothesis B. A fault occurring in the upstream grid determines the disconnection of the microgrid. The microgrid is operating in islanding state during the time interval t = 64–80 (i.e. between hours 16:00 and 20:00).

The results of the optimization model related to thermal engine operation and battery discharge, as well as the model input PV production, are illustrated in

Fig. 5. The optimization model results related to consumption schedule within the microgrid are illustrated in Fig. 6.

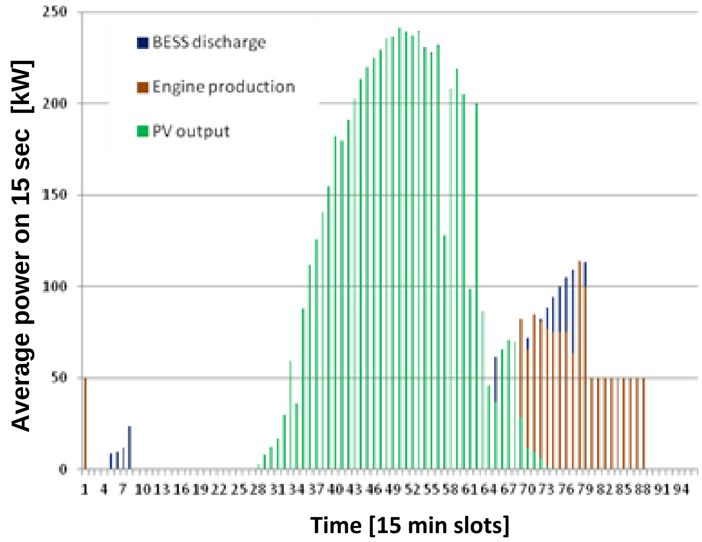

Fig. 5. Resulting generation schedule within the microgrid, *case I*, *hypothesis B*

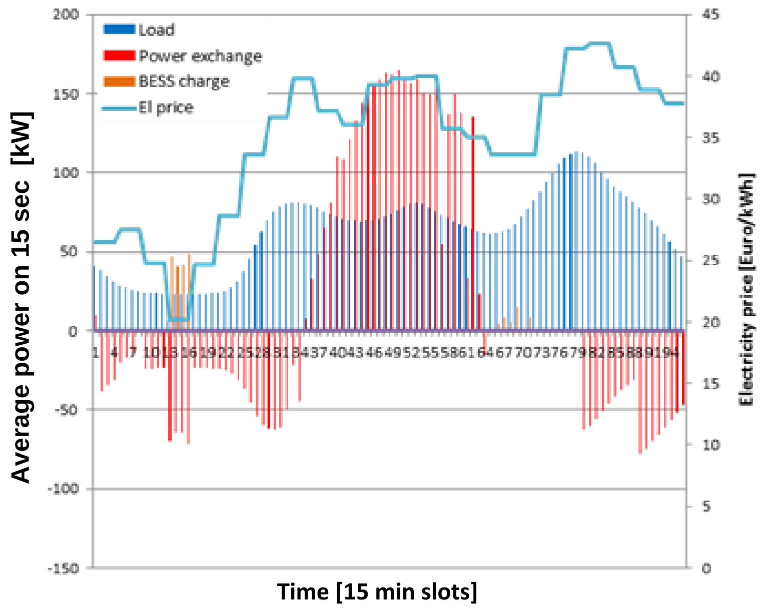

Fig. 6. Resulting consumption schedule within the microgrid, *case I*, *hypothesis B*

As it can be seen in Fig. 6, during the islanding operation, the upstream grid is no more offering support to balance the microgrid demand. As illustrated in Fig. 5, the thermal engine is switched on and is maintained in operation between hours 16:00 and 20:00. The storage energy system is discharged to balance the demand and to minimize the operational costs. After hour 21, the electricity price is decreasing and the thermal engine usage is lower. In the time interval t = 66–70, as the microgrid generation is exceeding the demand, the excess production is used for charging the storage energy system. After hour 21, is more economical to purchase the required electrical energy from the upstream grid instead of locally generating with the thermal engine.

Case II. In this case, the photovoltaic production is assumed that cannot be accurately forecasted. For considering the production errors, 20 production scenarios are generated to test the microgrid operation in each scenario. The generated scenarios and the forecasted values of PV production, for a production period between t = 26 and t = 74 (i.e. between hours 06:30 and 18:30), are illustrated in Fig. 7. From these 20 scenarios, for reducing the computational burden, by applying mathematical manipulation [23], only the most relevant 10 scenarios are used within the simulations. As in *case I*, it is considered that there is no constraint of transfer capacity between the microgrid and the upstream grid.

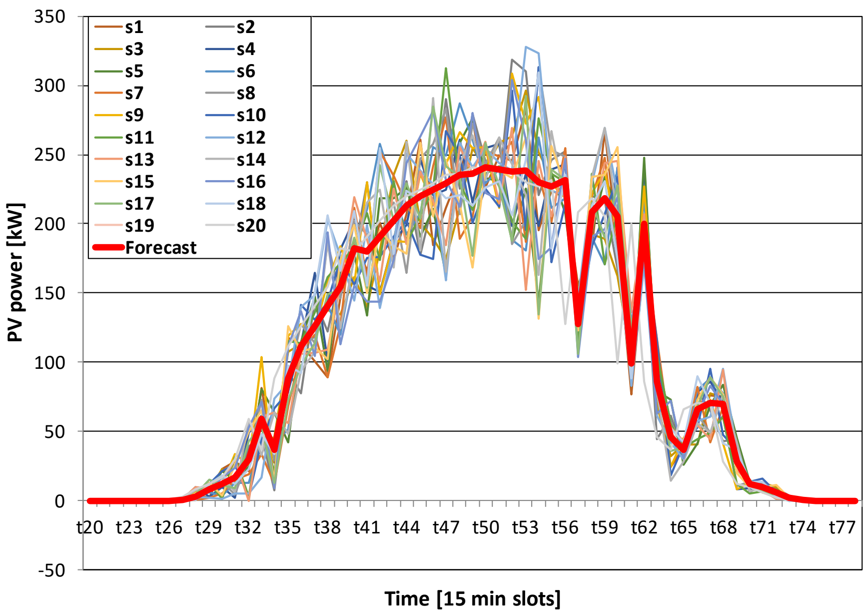

Fig. 7. Generated scenarios and forecasted values of PV production.

Hypothesis A. The microgrid is operating during the 24 hours analysis horizon interconnected with the upstream grid. The results of the optimization model regarding exchanged energy with the upstream grid are illustrated in Fig. 8. The exchanged energy with the upstream grid is settled such that to minimize the microgrid operational costs function of the electricity market price and before the PV production scenarios are occurring. Thus, it is independent of the scenario occurrence.

The optimization model results related to thermal energy scheduling, in each of the 10 scenarios, are illustrated in Fig. 9. During midday, for scenarios where the PV production is low and the electricity price is high the thermal engine can be switched on. The costs associated with the thermal engine operation are lower than the revenues obtained from selling energy in the upstream grid. In addition, the storage energy system is discharging such that to balance the load demand and to obtain the maximum revenue from selling energy to the upstream grid, as shown in Fig. 10. At time instant t = 79, when the electricity price is highest, the thermal engine is turned on and the storage system is fully discharged such that to sell energy to the upstream grid. This can be observed also in Fig. 10. The storage system charging schedule, for each PV production scenario, is illustrated in Fig. 11. As it can be observed, at time instant t = 13, when the electricity price is lowest, the storage system is fully charged.

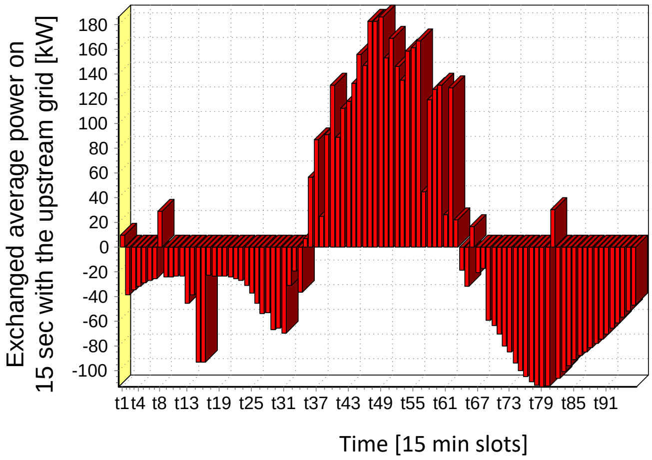

Fig. 8. Resulting exchanged energy with the upstream grid, *case II, hypothesis A*

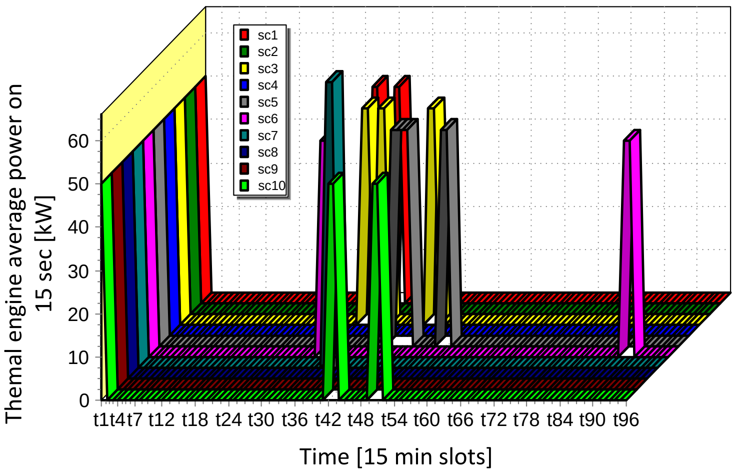

Fig. 9. Resulting thermal engine production schedule, *case II*, *hypothesis A*

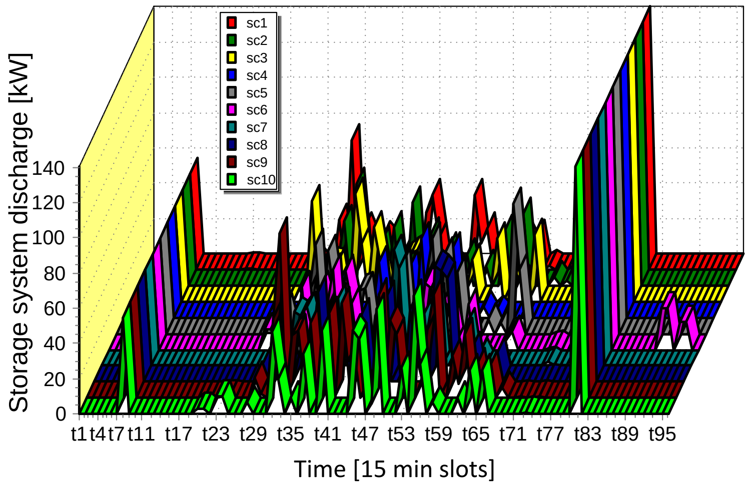

Fig. 10. Resulting storage system discharging schedule, *case II*, *hypothesis A*

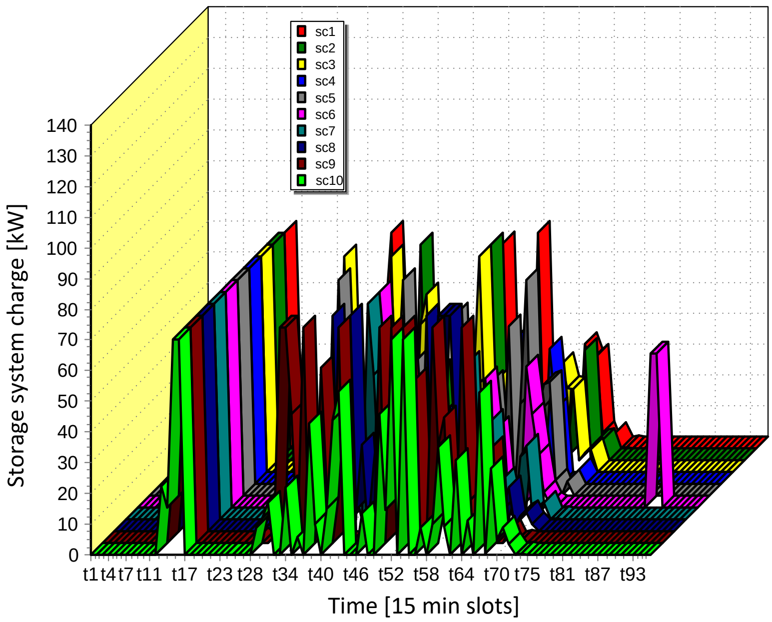

Fig. 11. Resulting storage system charging schedule, *case II*, *hypothesis A*

Hypothesis B. After a fault occurrence in the upstream grid, the disconnection of the interconnection breaker between the microgrid and the upstream grid is achieved. The microgrid is operating in islanding state during the time interval t = 64–80 (i.e. between hours 16:00 and 20:00). The minimum demand for the 24 hours horizon is considered to be equal as in *case II*, *hypothesis A*.

The exchanged energy with the upstream grid resulting after application of the optimization model is illustrated in Fig. 12. As shown, the period with zero exchanged energy is clearly observable. Figure 13 illustrates the operation of the thermal engine for supplying the demand. As it can be observed, during the islanding operation and under different scenarios, the thermal engine can operate at its maximum capacity. For the 24 hours operating horizon, it can be seen that the thermal engines has more operating cycles, with additional costs inducing on the overall microgrid operation costs. The costs of thermal engine operation can be lower than the revenues from selling energy towards to main grid.

The storage energy system is discharging such that to balance the load demand and to obtain the maximum revenue from selling energy to the upstream grid, as shown in Fig. 14. As shown, during the 24 hours the number of cycles of discharge-charge is higher than in hypothesis A. This can lead to the storage system lifecycle decay and additional costs for the microgrid. Under each PV production scenario, the storage system charging schedule is illustrated in Fig. 15.

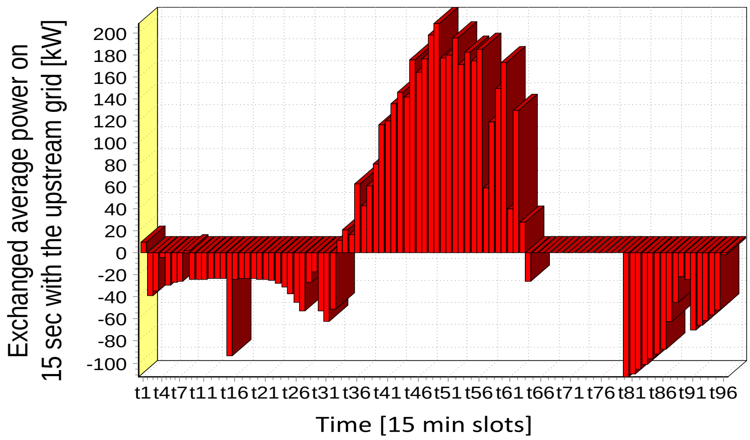

Fig. 12. Resulting exchanged energy with the upstream grid, *case II*, *hypothesis B*

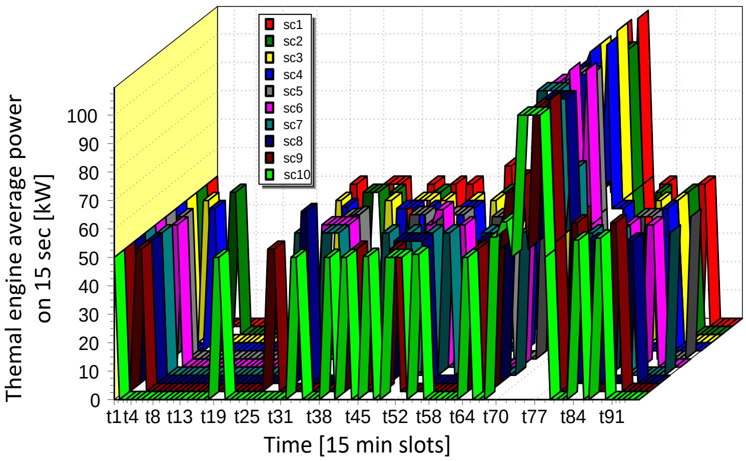

Fig. 13. Resulting thermal engine production schedule, *case II*, *hypothesis B*

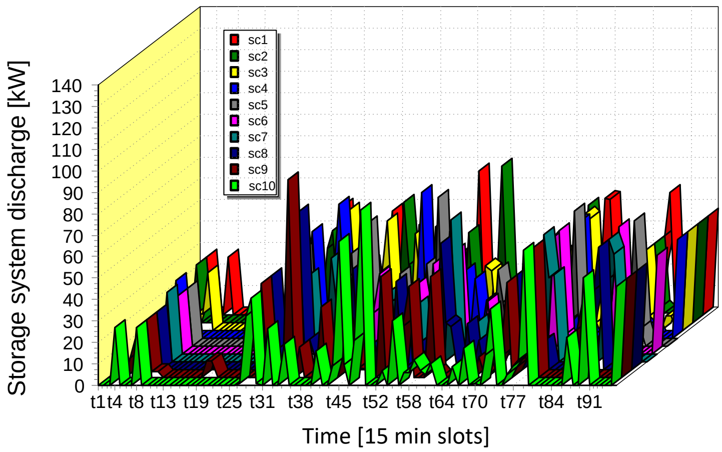

Fig. 14. Resulting storage system discharging schedule, *case II*, *hypothesis B*

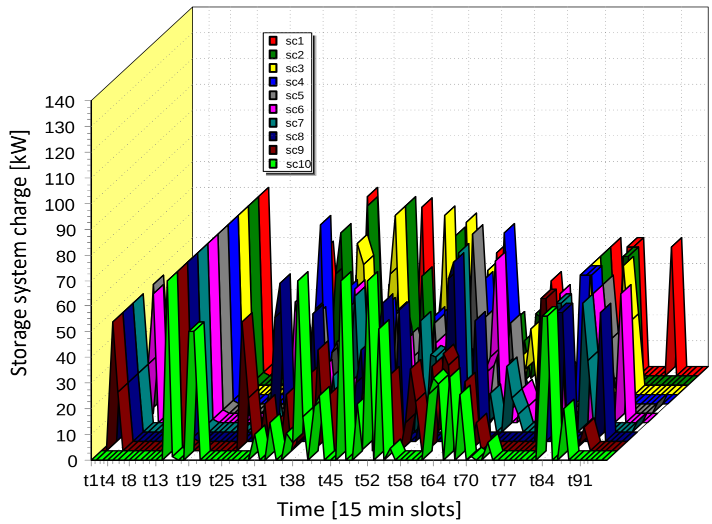

Fig. 15. Resulting storage system charging schedule, *case II*, *hypothesis B*

Table 2 reports the obtained objective function results of the optimization objective models applied to microgrid 24 hours operation. The reported results are obtained considering the perfectly accurate PV forecast (*case I*) and under various PV productions scenarios (*case II*). The microgrid is operating grid-connected (*hypothesis A*) and in case of fault occurrence leading to islanding operation for a specific period (*hypothesis B*). Figure 16 illustrates the variation of objective function Cost. It can be clearly observed that the uncertainty of PV production infeeds on the microgrid operation involving addition costs and passing from a negative value (profit) to positive ones (expenses). Figure 17 illustrates the variation of the objective function in each scenario for case study *I* and *II* under *hypothesis A*, respectively *hypothesis B*.

Table 2

Objective function Cost results (Euros)

Hypothesis \ Case study	*I*	*II*
A	– 64	21
B	128	264

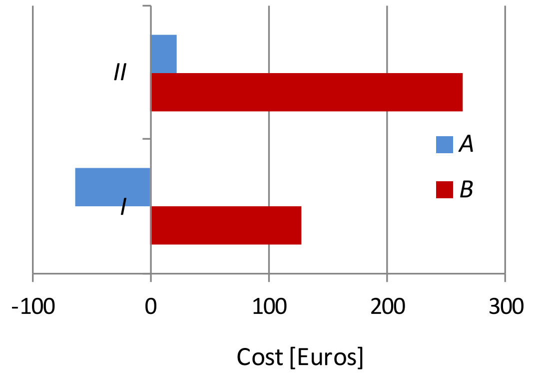

Fig. 16. Objective function *Cost* variation

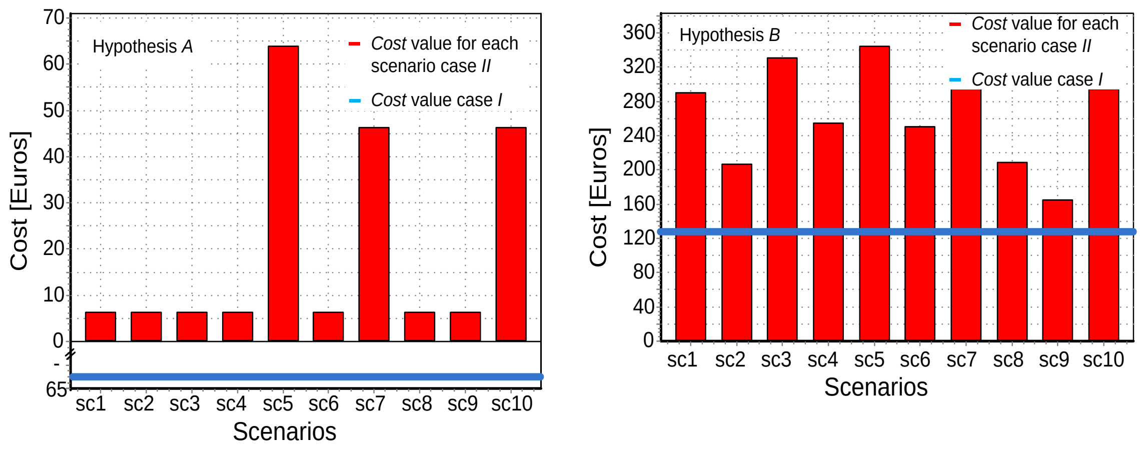

Fig. 17. Variation of objective function *Cost* values for each scenario, for *case I* (in blue) and *case II* (in red), under *hypothesis A* (left) and *hypothesis B* (right).

5. Conclusions

In this paper, an optimization model for minimizing operational costs of a microgrid was mathematically formulated. The microgrid is composed of a dispatchable thermal unit, a photovoltaic source, a storage energy system, critical and interruptible loads. The characteristic electrical data of the sources and loads within the microgrid are based on real data obtained from the producers. The PV production is based on recorded measurements. For accounting the fast dynamic behavior of PV systems, the microgrid operation analysis is made with 15 minutes time slots for 24 hours.

The microgrid can operate in grid-connected mode with the upstream power systems, or in islanding operation mode following a fault occurrence in the mains supply. The former one represents *hypothesis A*, while the latter one represents *hypothesis B*. The microgrid can exchange unlimited energy with the upstream power system function of the microgrid internal conditions and electricity price of the day-ahead market.

The optimization problem is formulated considering the PV production perfectly known, and the microgrid operation is optimized under these conditions (*case I*). The PV production forecasting errors can incur important additional operation costs. Thus, a stochastic optimization problem is formulated considering uncertainty scenarios of PV production (*case II*).

For grid-connected mode and stochastic optimization model, sudden changes in PV production can be compensated by local generators (storage system or thermal engine) with possible additional costs, especially when the electricity market price is high. Under islanding operation mode, the costs are increasing as load shedding and PV curtailment are highly penalized.

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