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Rémy Rigo-Mariani, Bruno Sareni, Xavier Roboam. Fast Power Flow Scheduling and Sensitivity Analysis for Sizing a Microgrid with Storage. 11th International Conference on Modeling and Simulation of Electric Machines, Converters and Systems (ELECTRIMACS'2014), May 2014, Valencia, Spain. pp. 275-280. hal-01015345

HAL Id: hal-01015345
https://hal.science/hal-01015345

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To cite this version : Rigo-Mariani, Rémy and Sareni, Bruno and Roboam, Xavier Fast Power Flow Scheduling and Sensitivity Analysis for Sizing a Microgrid with Storage. (2014) In: 11th International Conference on Modeling and Simulation of Electric Machines, Converters and Systems (ELECTRIMACS'2014), 19 May 2014 - 22 May 2014 (Valencia, Spain).

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FAST POWER FLOW SCHEDULING AND SENSITIVITY ANALYSIS FOR SIZING A MICROGRID WITH STORAGE

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Abstract - This paper proposes a fast strategy for optimal dispatching of power flows in a microgrid with storage. The investigated approach is based on the use of standard Linear Programming (LP) algorithm in association with a coarse linear model of the microgrid. The resulting computational time is compatible with simulations over long periods of time allowing the integration of seasonal and stochastic features related to renewable energies. By using this fast scheduling strategy over a complete year of simulation, the microgrid cost effectiveness is considered. Finally, a sensitivity analysis is carried out in order to identify the most influent parameters that should be considered in a sizing loop. Different microgrid configurations are also investigated and compared in terms of cost-effectiveness.

Keywords – Microgrid, storage, optimal scheduling; linear programming, dynamic programming

1. INTRODUCTION

With the growing number of renewable energy sources the power grid topology has evolved and it could be now described as an aggregation of several microgrids both consumer and producer [1]. For those "prosumers", a classical strategy consists in selling all the highly subsidized production at important prices while all consumed energy is purchased [2]. Smarter operations become possible with the development of energy storage technologies and evolving price policies [3]. Those operations would aim at reducing the electrical bill taking account of consumption and production forecasts as well as the different fares and possible constraints imposed by the power supplier [4]. The microgrid considered in the paper is composed of a set of industrial buildings and factory with a subscribed power P_s of 156 kW and a PV generator with a peak power of 175 kW (Fig. 1*a*). A 100 kW/100 kWh storage consisting in the association of ten high-speed flywheels is also introduced. The strategy chosen to manage the overall system is based on a daily off-line optimal scheduling of power flows for the day ahead. Then, in real time, an on-line procedure adapts the same power flows in order to correct errors between forecasts and actual measurements [5]. Several algorithms have been investigated in previous works to perform the off-line optimization for a single day but the high computational times observed did not comply with a sizing procedure that would require many runs of the procedure over long periods of time (e.g., weeks, months, years) [6]. The present study focuses on a faster approach consisting in two steps. Firstly, a basic Linear Programming (LP) algorithm solves the cost minimization problem with a coarse linear model of the system as in [7]. Then, a second procedure adapts the obtained solutions to comply with the requirements of a finer nonlinear model. The paper is organized as follows. The first section describes both coarse and fine models used to represent the system and the various considered hypotheses especially concerning the cost model. Then, the second section presents the fast optimization approach and gives details about adaptation of the control references resulting from the LP optimization. In section 4, the results obtained on a test day are presented, by considering particular production and consumption forecasts and according to given energy price policies and subscribed power. A sensitivity analysis is then performed in order to estimate the most significant parameters that could be considered in a sizing procedure for a microgrid with storage.

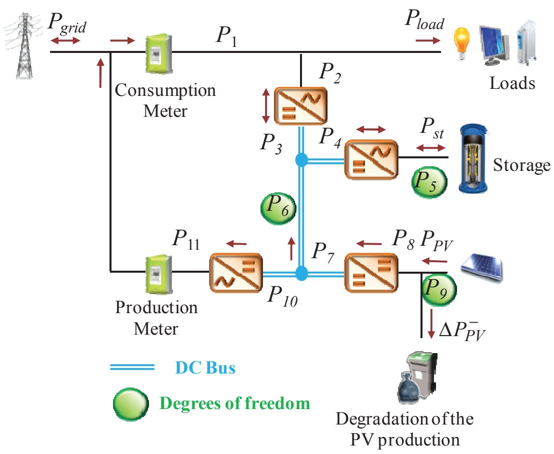

Fig. 1: Considered microgrid and power flows

2. MODEL OF THE STUDİED MİCROGRİD

2.1. POWER FLOW MODEL AND DEGREES OF FREEDOM

As illustrated in Fig. 1, the components are connected though a common DC bus. Voltages and currents are not considered so far. The micro grid sizing (cable length) is very limited. Thus losses within the lines can be aggregated with converters efficiencies. Furthermore, the paper focuses on the optimal scheduling of the system without considering a real-time management strategy (i.e. voltage/current control). The study refers to the optimization of active power flows $P_i(t)$. Due to the grid policy, three constraints have to be fulfilled at each time step t. The power flows thought the meter have to remain unidirectional (i.e. $P_1(t)$ 0 and $P_6(t)$ 0). In a addition, $P_6(t)$ 0: to avoid illegal use of the storage device, it cannot discharge itself through the production meter

The equations between all power flows are generated using the graph theory and the incidence matrix [8]. As illustrated in Fig. 1*b*, three degrees of freedom are required to manage the whole system knowing production and consumption:

- $P_5(t) = P_{st}(t)$: the power flowing from/to the storage unit (defined as positive for discharge power)

- $P_6(t)$: the power flowing from the PV array**s** to the common DC bus

- $P_9(t) = \Delta P_{PV}$ denotes the possibility to decrease the PV production (MPPT degradation) in order to fulfill possible grid constraints.

The load control is not investigated in the study but could also be considered in further works as an additional degree of freedom with the possibility of shedding or delaying some consumptions.

2.2. EFFİCİENCİES AND FİNE MODEL

A "fine model" is defined taking account of efficiencies of power converters (typically 98 %) and storage losses. These losses are computed with the state of charge *SOC* (in %) and the power P_{st} using a function $P_{loss}(SOC)$ and calculating the efficiency with a fourth degree polynomial $\eta_{FS}(P_{st})$ (see (1)) depending on the direction of the power flow P_5 (i.e; charge or discharge conditions). Both P_{loss} and η_{FS} functions are extracted from measurements provided by the manufacturer [9].

$$P_{FS}(t) = P_{loss}\left(SOC(t)\right) + P_5(t) \times \eta_{FS}\left(p_5(t)\right) \qquad (1)$$

Once the overall efficiency is computed, the true power P_{FS} associated with the flywheel is calculated as well as the *SOC* evolution using the maximum stored energy E_{FS} (in kWh), the time step Δt (typically 1 hour for the off-line optimization) and the control reference P_5.

$$SOC(t+\Delta t) = SOC(t) - \frac{P_{FS}(t)}{E_{FS}} \times \Delta t \times 100 \qquad (2)$$

Another coefficient K_{FS} (in kWh/h) is also introduced to estimate the self-discharge of the flywheels when they are not used (i.e. $P_5 = 0$):

$$SOC(t+\Delta t) = SOC(t) - \frac{K_{FS}}{E_{FS}} \times \Delta t \times 100 \qquad (3)$$

2.3. DEFİNİTİON OF A COARSE LİNEAR MODEL

In a second step, a coarse model is developed in order to speed up the solving by using a linear formulation of the problem. Firstly, the converter efficiencies are neglected which leads to the following simplifications:

$$\begin{cases} P_2(t) = P_3(t) \\ P_4(t) = P_5(t) \\ P_7(t) = P_8(t) \\ P_{10}(t) = P_{11}(t) \end{cases} \qquad (4)$$

In this model, storage losses are also neglected as well as the self-discharge. Thus, the *SOC* is simply computed at each time step of duration Δt = 1h:

$$SOC(t+\Delta t) = SOC(t) - \frac{P_5(t)}{E_{FS}} \times \Delta t \times 100 \qquad (5)$$

3. A FAST OPTİMİZATİON BASED ON LP

3.1. STANDARD COST MİNİMİZATİON

The microgrid has to be run in order to minimize the electrical bill expressed as the différence betwen the purchased energy at a rate $C_p(t)$ (€/kWh) and the sold one at a rate $C_s(t)$ (€/kWh). If the power flowing through the consumption meter is greater than the subscribed power P_s, penalties have to be paid with C_{ex} (€/h) (6). The references of the power flows associated with the degrees of freedom over the simulated period are computed in a vector $\mathbf{P_{ref}} = [\mathbf{P_5}\ \mathbf{P_6}\ \mathbf{P_9}]$. Once $\mathbf{P_{ref}}$ is determined, all other power flows are computed (by means of linear relationships) from forecasted values of consumption and production. Then $\mathbf{P_1}$ and $\mathbf{P_{11}}$ are known and the cost function is calculated as follows for a 24 hours simulated period:

$$C = \sum_{t=0}^{24\text{h}} P_1(t).C_p(t) - P_{11}(t).C_s(t) + \delta(t).C_{ex}$$
$$\text{with } \begin{cases} \delta(t) = 0 \text{ if } P_1(t) < P_s \\ \delta(t) = 1 \text{ if } P_1(t) > P_s \end{cases} \qquad (6)$$

3.2. LP APPLIED TO A COARSE MODEL AND REFERENCES CORRECTION

In previous works, several algorithms have been used to perform the off-line optimization for the fine model [6]. In this section, the standard fast LP is considered to solve the problem related to the coarse model developed in section 2. Such linear approach aims at decreasing CPU time. Using LP imposes to have a linear cost (expressed with a matrix $\mathbf{C_L}$) and linear constraints (expressed though a matrix $\mathbf{A}$ and a vector $\mathbf{B}$). Taking account of the exceeding of the subscribed power is strongly nonlinear. Thus, a transformation of the linear problem has to be performed and it leads among other to add another variable denoted as $\boldsymbol{\delta}$. to the vector with the references. The procedure is then run according to [9]:

$$\mathbf{P}^* = \begin{bmatrix}\mathbf{P_5^*} & \mathbf{P_6^*} & \mathbf{P_9^*} & \boldsymbol{\delta}\end{bmatrix} = \arg\min_{\mathbf{P}}\left(\mathbf{C_L}.\mathbf{P}\right) \quad \text{with } \mathbf{A}.\mathbf{P}^* \leq \mathbf{B} \tag{7}$$

The upper ($\mathbf{u_b}$) and lower ($\mathbf{l_b}$) bounds of decision variables are expressed using the column vector $\mathbf{J_n}$ with n coefficients equal to 1, where n is the number of simulated time steps, i.e. $n = 24$ for a whole day with Δt = 1h. In particular, the limits of $\boldsymbol{P_5}$ refer to the maximum charge and discharge powers of the storage with $P_{st\_min} = -100$ kW and $P_{st\_max} = 100$ kW.

$$\begin{cases}\mathbf{l_b} = \begin{bmatrix}P_{st\_\min}\times\mathbf{J_n} & 0\times\mathbf{J_n} & 0\times\mathbf{J_n} & 0\times\mathbf{J_n}\end{bmatrix}\\ \mathbf{u_b} = \begin{bmatrix}P_{st\_\max}\times\mathbf{J_n} & \mathbf{P_{PV}} & \mathbf{P_{PV}} & 1\times\mathbf{J_n}\end{bmatrix}\end{cases} \tag{8}$$

The previous cost function $C(\mathbf{P_{ref}})$ is developed for the coarse model according to the decision variables $\mathbf{P_5}$, $\mathbf{P_6}$, $\mathbf{P_9}$ and $\boldsymbol{\delta}$ for the linear problem. The nonlinear term is removed to obtain the vector $\mathbf{C_L}$ used in the LP optimization.

$$C(\mathbf{P}) = \sum_{t=0}^{24\text{h}}\begin{pmatrix}-P_5.C_p + P_6.\left(C_s - C_p\right)\\ +P_9.C_s + P_{load}.C_p\\ -P_{PV}.C_s + \delta.C_{ex}\end{pmatrix} \tag{9}$$

$$\begin{aligned}&\mathbf{C_L}\times\mathbf{P} = C(\mathbf{P}\ ) - \mathbf{P_{load}}\times\mathbf{C_p}^{\mathbf{T}} + \mathbf{P_{PV}}\times\mathbf{C_s^T}\\ &\mathbf{C_L} = \begin{bmatrix}-\mathbf{Cp}^{\mathbf{T}} & (\mathbf{C_s}^{\mathbf{T}} - \mathbf{C_p}^{\mathbf{T}}) & \mathbf{C_s}^{\mathbf{T}} & C_{ex}\times\mathbf{J_n}\end{bmatrix}\end{aligned} \tag{10}$$

The constraint matrix $\mathbf{A}$ and vector $\mathbf{B}$ are built by concatenating the matrices $\mathbf{A_i}$ and $\mathbf{B_i}$ used to express each grid requirement [6]. Considering the penalties due to the overshoots when P_s is exceeded imposes the values for δ. That is performed using the folowing constraint at each time step where M denotes the maximum expected value for (P_1-P_s) (set to 250 kW here), $\mathbf{I_n}$ and $\mathbf{0_n}$ are the nxn identity and zero matrices.

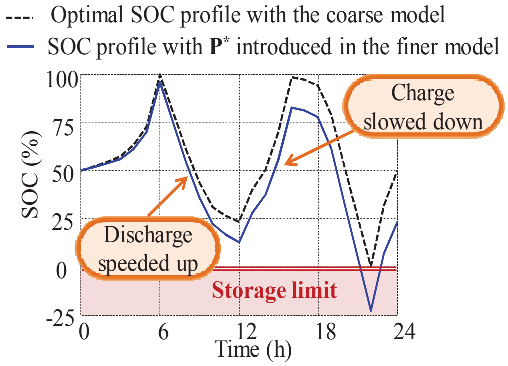

Fig. 2: SOC constraint violation with the fine model

$$\begin{cases}\left(P_1(t) - P_s\right) - M.\delta(t) \leq 0 \quad \text{for } t \in [0..24\text{h}]\\ -P_5(t) - P_6(t) - M.\delta(t) \leq P_s - P_{load}(t)\\ \mathbf{A_i}\times\mathbf{P} \leq \mathbf{B_i}\\ \text{with } \mathbf{A_i} = \begin{bmatrix}-\mathbf{I_n} & -\mathbf{I_n} & \mathbf{0_n} & -M\times\mathbf{I_n}\end{bmatrix}\\ \text{and } \mathbf{B_i} = P_s\times\mathbf{J_n} - \mathbf{P_{load}}\end{cases} \tag{11}$$

The dispatching problem defined in the previous subsection can quickly be solved in less than one second (for 24h to be planned) using a standard LP algorithm e.g. the Matlab© function *linprog* with sparse matrices. Some preliminary results show that the obtained solutions obviously do not comply with requirements of the fine microgrid model. Fig. 2 illustrates a case for which the solution $\mathbf{P}^*$ obtained with LP is simulated with fine model equations. It should be noted that a deep discharge occurs at around 10 p.m. Due to losses, the *SOC* goes down to –25 % with the fine model while it remains to 0 % with the coarse linear model. Indeed, taking account of losses also leads to slow down the storage charge and to speed up the storage discharge. Therefore, the control references ($\mathbf{P}^*$) relative to the degrees of freedom obtained with the LP have to be adapted in order to comply with the fine microgrid model. This is performed by means of a step by step correction which aims at minimizing the cost while aligning the *SOC* computed from the fine model with the one resulting from the LP optimization [6] Typically, the CPU time related to this local correction procedure is less than one second over a day of simulation while the other tested global algorithms (i.e. genetic algorithm, dynamic programming and trust region) lasted up to 2 h for one day of simulation.

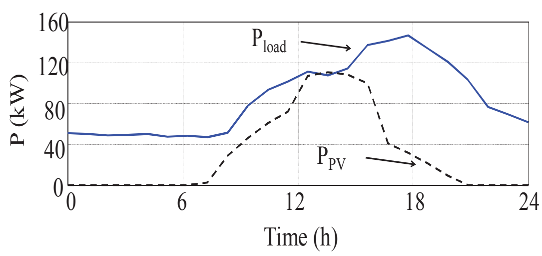

Fig. 3: Forecasted consumption and production

4. Test Results

4.1. Input Data

In this subsection, the algorithm is tested on a single day considering two different values for the subscribed power P_s. The consumption profile is extracted from data provided by the microgrid owner while the production estimation is based on solar irradiation forecasts, computed with a model of PV arrays [11]. Energy prices result from one of the fares proposed by the French main power supplier [12] increased by 30%. Thus, the purchase cost C_p has night and daily values with 0.10 €/kWh from 10 p.m. to 6 a.m. and 0.17 €/kWh otherwise. Sale fare C_s is set to 0.1 €/kWh which corresponds to the price for such PV plants. C_{ex} = 14 €/h and the prices related to the subscribed power is not considered here. It will be significant when a whole year will be simulated in order to find an optimal value (see section 5).

4.2. Validation on a Single Day

The off-line optimization is performed with the developed algorithm for two different values of P_s (i.e P_s = 156 kW and P_s = 95 kW). The obtained results with storage (WS) are shown in the Table I and compared with cases without storage nor optimal power dispatching (NS). On a single day, the computational time is less than one second. For the two values of P_s adding a storage device and an optimal dispatching strongly decreases the cost on the considered day. Results show that there is no sold energy in order to favor the self-consumption. With a lower subscribed power, the number of overshoots is also reduced and the penalty cost goes down to 14 € instead of 140 €. Profiles for the *SOC* and the optimal power flowing through the consumption meter (i.e. P_1) are illustrated on Fig 4. The optimal power dispatching aims at minimizing consumption when prices are high (Fig 4*a*). Thus, the storage is firstly charged before 6 a.m. Then, the solar production is used to feed loads while the surplus charges the flywheel. At the end of the day, when there is no solar radiation any long, the storage discharge itself until consumption prices become lower at 10 p.m. (Fig 4*b*). The subscribed power of 156 kW is never reached but when it decreases to 95 kW the optimal dispatching lowers the number of overshoots (Fig 4*a*) as well as the storage charge during the afternoon is greater (Fig 4*b*).

I. Results on a single day for different values of P_s

P_s (kW)	156		95	
Storage	NS	WS	NS	WS
Purchase (€)	332.7	202.2	332.7	202.8
Sale (€)	73.5	0.0	73.5	0.0
Penalty (€)	0.0	0.0	140.0	14.0
TOTAL(€)	259.2	**202.2**	399.2	**216.8**

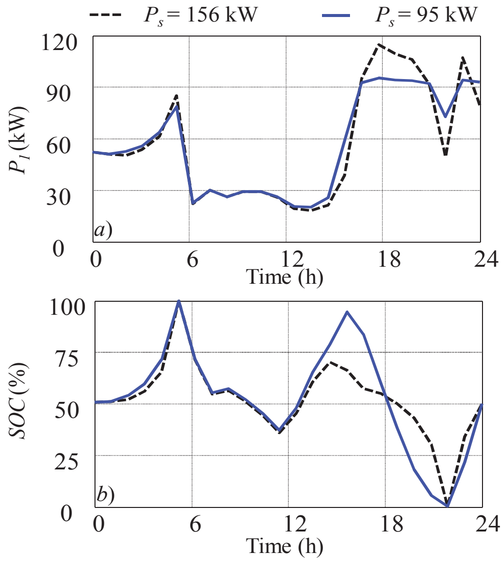

Fig. 4: Optimal profiles with two P_s

5. Sizing Loop

5.1. Sensitivity Analysys

The developed algorithm has been previously tested on a single day. This section focuses on simulations of a whole year taking the stochastic and seasonal features of PV production and load consumption into account. This "long term vision" is essential to investigate a sizing loop aiming at estimating the best configuration for the microgrid depending on the various costs (Fig. 5). To estimate yearly costs, component prices have to be considered. PV arrays are associated with a cost of 0.6 €/Wc [13] and the flywheels with 1500 €/kWh [14]. A lifetime of 20 years is expected for the installation. The yearly electrical bill also depends on the value of P_s with a cost of 35.3 €/kW [12]. Thus, given yearly forecasted consumption and production and for pre-determinated prices policy, two variables are identified as the parameters to define the size of the microgrid: E_{FW} (kWh) the maximum stored energy in the flywheels and

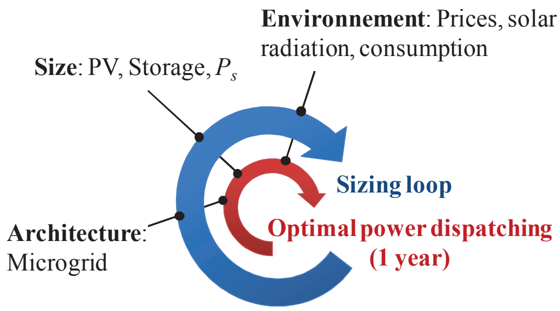

Fig. 5: Optimal dispatching in a sizing loop

P_{PV_max}(kW) the maximum power of the PV generator. Additional management parameters are also introduced: the subscribed power P_S (kW) and the number of successive days $T_{schedule}$ on which the scheduling is extended. For $T_{schedule}$ = 1 day as previously, 365 successive optimizations have to be performed to simulate a year. It should be noted that the computational time of the power flow scheduling strongly increases when the simulated period becomes longer as the number of variables in the LP problem is greater. The last studied variable denoted SOC_0 represents the initial and final SOC value in the optimization loop (50 % previously). Bounds are arbitrary chosen for those five variables:

- 0 kWh < E_{FW} < 1500 kWh
- 0 kW < P_{PV_max} < 500 kW
- 100 kW < P_s < 250 kW
- 1 day < $T_{schedule}$ < 120 days
- 0 % < SOC_0 < 100 %

A sensitivity analysis is performed using a full factorial design [15]. The weight coefficient of the main effects (a_i) of the variables and their interactions (b_i) are studied as for the following example with a two parameter function $y = f(x_1,x_2)$ modelled as follow:

$$y = \hat{y} + a_1 \times x_1 + a_2 \times x_2 + b_1 \times x_1.x_2 \qquad (12)$$

In (12), $\hat{y}$ is the average value of the function with the different points y_i given by the design of experiments when the values are at their higher (+1) or lower (-1) bounds. The weight a_i and b_i are then computed using the columns of the Table II and N the number of experiments (i.e. 4 in a problem with two parameters):

$$\begin{cases} a_i = \mathbf{a_i}^{\mathbf{T}}.\mathbf{y} / N \\ b_i = \mathbf{b_i}^{\mathbf{T}}.\mathbf{y} / N \end{cases} \qquad (13)$$

II. Full factorial design of experiments

$a_1=x_1$	$a_2=x_2$	$b_1=x_2\,x_1$	Y
+1	+1	+1	y_1
+1	-1	-1	y_2
-1	+1	-1	y_3
-1	-1	+1	y_4

For five parameters, as for the studied problem, the absolute values of coefficients are plotted in Fig 6. The corresponding parameters (effect/interactions) are underlined. The coefficients referring to the values of E_{FW}, P_{PV_max}, and P_s appear to be the most influent. In a first approximation, only those three variables could be considered when studying different sizing cases.

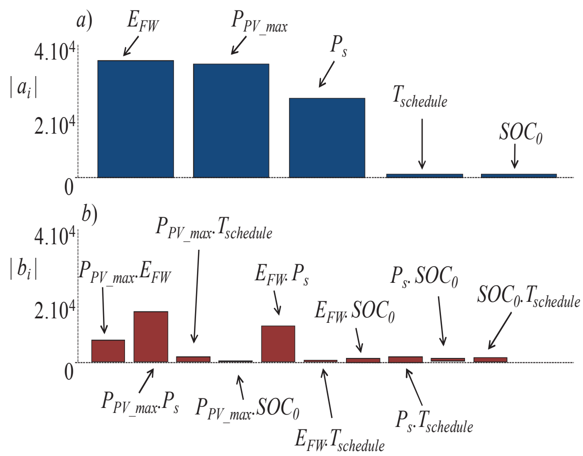

Fig. 6: Sensitivity analysis - *a*) factor effect - *b*) interaction effect

5.2. CASE ANALYSİS

Table III gives the results returned when a year is simulated with the optimal power dispatching with different values of the three significant sizing parameters. As in the previous section, $T_{schedule}$ is set to 1 day and SOC_0 to 50 %. The resulting computational time is close to 10 min for each investigated sizing (note that ~3 days of computation would be necessary to optimize power management by means of dynamic programming algorithm). The costs for the components and the purchase/sold energy are expressed in k€. The second column refers to a case for which only the consumption is considered. Adding a storage device allows to reduce the penalty by restricting as much as possible the exceeding of P_s. In the same time, the cost for purchased energy is lowered with load shifting during night hours when prices decrease. But the resulting gain does not compensate the investment cost. With a low investment cost and a good retribution price, a solar generator improves the yearly results of the microgrid. Adjusting the subscribed power also improves the yearly cost and an optimal value has to be found.

III. Results for different sizing parameters (k€)

E_{FW} (kWh)	0	100	100	100
P_{PV_max} (kW)	0	0	175	175
P_s (kW)	95	95	95	156
Cost FW	0	7.5	7.5	7.5
Cost PV	0	0	5.2	5.2
Cost P_s	3.3	3.3	3.3	5.5
Purchase	101.6	100.6	87.6	89.3
Sale	0	0	2.6	2.6
Penalty	27.8	24.8	14.1	2.3
TOTAL:	132.7	136.2	115.2	**107.3**

CONCLUSIONS

The study carried out in this paper aims at proposing a fast procedure in terms of computation time that could be used to investigate cost-effectiveness of a microgrid with storage. In previous works, efficient algorithms have been developed to perform the daily scheduling of power flows. However, the main drawbacks of these methods reside in their computational times that become prohibitive if the microgrid has to be simulated over a long period of time. To overcome this problem, a fast optimization approach based on LP has been proposed. This approach consists in two successive steps. Firstly, a coarse linear model of the microgrid is exploited to solve the optimal dispatching with a classical LP algorithm. Secondly, control references optimized with the coarse model are adapted in order to comply with a finer model of the microgrid which takes account of nonlinear features (i.e. efficiencies). The performance of this approach with regard to energy cost minimization and computational time reduction has been shown on a particular test day. Moreover, the fast CPU time resulting from this optimal dispatching method has allowed us to simulate the microgrid over a whole year and to investigate several configurations. The obtained results have shown that the interest of using a storage unit is closely linked to the economical context. Future studies will be focused on the same issue with other kind of storage technologies such as Li-ion batteries for which cycling effect would have to be included in the cost function. Finally, the fast control algorithm may offer the ability of achieving systemic design of microgrids integrating sizing optimization loop with power dispatching optimization by taking account of system environment and requirements.

ACKNOWLEDGMENT

This study has been carried out in the framework of the SMART ZAE national project supported by ADEME (Agence de l'Environnement et de la Maîtrise de l'Energie). The authors thank the project leader INEO-SCLE-SFE and partners LEVISYS and CIRTEM.

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