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Optimal Power Flow model with energy storage, an extension towards large integration of renewable energy sources. ⋆

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Abstract: The integration of renewable energy sources (RES) into modern electrical grids contributes to satisfying the continuously increasing energy demand. This can be done in a sustainable way since renewable sources are both inexhaustible and non-polluting. Different renewable energy devices, such as wind power, hydro power, and photovoltaic generators are available nowadays. The main issue with the integration of such devices is their irregular generation capacity (in particular for wind and solar energy). Therefore energy storage units are used to mitigate the fluctuations during generation and supply. In this paper we formulate a model for the Alternate Current Optimal Power Flow (ACOPF) problem consisting of simple dynamics for energy storage systems cast as a finite-horizon optimal control problem. The effect of energy storage is examined by solving a Norwegian demo network. The simulation results illustrate that the addition of energy storage, along with demand based cost functions, significantly reduces the generation costs and flattens the generation profiles.

Keywords: AC optimal power flow, power system economics, power transmission, power distribution control, renewable energy sources

1. INTRODUCTION

The electric power industry has lived a significant expansion and growth over the course of the past two decades. The penetration of renewable sources, such as wind, hydro and solar, is increased by the requirements of the governments in order to achieve goals related to emission reduction and energy independence. However, their intermittent nature may have negative effects on the entire grid. One of the most viable solutions is the integration of Energy Storage Systems (ESS), which mitigates against fluctuations in generation and supply. However, they add another degree of complexity to the scheduling of power flows. Thus our interest in improving algorithms for power flow optimization.

To achieve both operational reliability and financial profitability, a more efficient utilization and control of the existing transmission and distribution system infrastructures is required. All these factors contribute to the increasing need of fast and reliable optimization methods that can address both security and economical issues simultaneously, supporting power system operation and control.

In this scenario, the microgrid concept is a promising approach. Usually described as a confined cluster of loads, storage devices, and small generators, these autonomous networks can operate in island mode or in parallel with the main grid to supply power to the loads, Lasseter and Paigi (2004), Hatziargyriou et al. (2007). In addition a microgrid can purchase and sell power from the public distribution grid through the Point of Common Coupling PCC. The optimization of the microgrid operations is extremely important in order to manage its energy resources in a cost-efficient way, Hatziargyriou et al. (2007), www.smartgrids.eu (2008).

The set of optimization problems in electric power systems engineering is known collectively as Optimal Power Flow (OPF). It is one of the most important problem regarding handling large-scale power systems in an effective and efficient manner and, it falls into the well-researched sub-fields of constrained nonlinear optimization. The OPF concept was first introduced by Carpentier (1962). He included the transmitted power problem in a simple optimal Economic Dispatch (ED). His work has been widely applied in power

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systems analysis, Momoh (1989); in addition see the surveys in Chowdhury and Rahman (1990); Huneault and Galiana (1991); Momoh et al. (1999a); K.S.Pandya (2008); Momoh (2001), for a broader view and details.

In general, OPF is a nonlinear optimization problem, which seeks to optimize the operation of an electric power system (power generation and transmission) while satisfying operational and physical constraints imposed by Kirchhoff's laws and functional limits on the decision variables, Momoh et al. (1999a). The solution technique for OPF problems was first proposed by Dommel and Tinney (1968) based on Newton-Raphson method. Since that time, several mathematical methods have been employed to solve OPF, such as linear, nonlinear, quadratic, mixed integer programming, interior-point methods and Newton-based methods, Huneault and Galiana (1991); Momoh (1989); Momoh et al. (1999b). The aim of OPF is to set the power network variables in order to meet the energy demand in the most economically manner, while simultaneously keeping all constraints within specific bounds, imposed on the physical systems.

This paper aims to formulate a model for the Alternate Current Optimal Power Flow (ACOPF) problem consisting of simple dynamics for energy storage systems. The ESS is needed to mitigate irregular generation from renewable energy sources while guaranteeing the network power balance.

There are several commercial software tools available to simulate and solve power flow problem, such as MATPOWER Zimmerman et al. (2011), PSAT Milano (2013), GridLabD (2013) and GAMS (2013). In our work, the solution of the ACOPF is modelled by using the software GAMS and InterPSS in a JAVA framework. The InterPSS choice has been motivated by the free and open source distribution of the simulation platform. In addition, InterPSS core can be integrated into custom made software/simulators in combination with GAMS to define and efficiently solve large scale optimization problems.

The paper is organized as follows. In Section 3 the nonlinear non-convex optimization problem is given, where microgrid components models are presented in details. Simulation results are shown in Section 4 and the effect of energy storage is examined by solving a Norwegian demo network. Finally, the conclusion and future work are presented.

2. NOMENCLATURE

Variables

C_i^g:	Cost function of generator at bus i [\$]
C_i^b:	Cost function of storage at bus i [\$]
$\tilde{S}_i^g$:	Complex power generated at bus i [MVA]
P_i^g:	Active power generated at bus i [MW]
Q_i^g :	Reactive power generated at bus i [MVAr]
$\tilde{S}_{ij}$:	Complex power flow from bus i to bus j [MVA]
P_{ij}:	Active power flow from bus i to bus j [MW]
Q_{ij}:	Reactive power flow from bus i to bus j [MVAr]
V_i:	Voltage magnitude at bus i [pu]
$\tilde{V}_i$:	Voltage phasor at bus i
$\tilde{I}_i$:	Current phasor at bus i
θ_i:	Voltage angle at bus i [°]
b_i:	State of Charge (SOC) of the storage unit at bus i [MWh]
r_i:	Power exchanged with the storage unit at bus i [MW]

Sets

$\mathcal{G}$:	Set of buses with generator
$\mathcal{D}$:	Set of buses with load
$\mathcal{R}$:	Set of buses with renewable generator
$\mathcal{B}$:	Set of buses with storage units
$\mathcal{N}$:	Set of all buses with cardinality n

Parameters

c_i:	Cost coefficients, bus i [\$/MWh]
c^p, c^s:	Purchasing/selling prices [\$/MWh]
c_j^b:	Storage cost coefficients, bus i [\$/MWh]
$\tilde{Y}_{ij}$:	Complex series admittance, line ij [pu]
$\tilde{Y}_{ij}^{Sh}$:	Complex shunt admittance, line ij [pu]
B_{ij}:	Series susceptance, line ij [pu]
G_{ij}:	Series conductance, line ij [pu]
B_{ij}^{Sh}:	Shunt susceptance, line ij [pu]
G_{ij}^{Sh}:	Shunt conductance, line ij [pu]
$\tilde{S}_i^d$:	Complex power load, bus i [MVA]
P_i^d:	Active power load, bus i [MW]
Q_i^d:	Reactive power load, bus i [MVAr]
$\tilde{S}_i^{res}$:	Complex renewable power, bus i [MVA]
P_i^{res}:	Renewable active power, bus i [MW]
Q_i^{res}:	Renewable reactive power, bus i [MVAr]
$P_{i\min}^g, P_{i\max}^g$:	Generator active power bounds, bus i [MW]
$Q_{i\min}^g, Q_{i\max}^g$:	Generator reactive power bounds, bus i[MVAr]
$S_{ij\,\max}$:	Rating of line ij [MVA]
$V_{i\,\min}, V_{i\,\max}$:	Min and max voltage magnitudes, bus i [pu]
$\theta_{i\min}, \theta_{i\max}$:	Minimum and maximum phases, bus i [°]
$\theta_{ij\max}$:	Maximum angle difference between bus i-j [°]
B_i:	Maximum storage unit capacity, bus i [MWh]
b_i^{loss}:	Storage energy loss, bus i [MWh]
r^{rated}:	Maximum power supplied by the storage [MW]
T:	Sampling time [h]

3. SYSTEM DESCRIPTION, MODELLING, CONSTRAINTS AND PROBLEM FORMULATION

The OPF formulation models the entire network (i.e. generators, loads, storage units and transmission lines). Furthermore, the interaction with the utility grid through the PCC or 'slack bus' needs to be modelled as well (here indicated with the index $i = 0$). Next sections are inspired by the idea developed in Gayme and Topcu (2011).

3.1 Storage Dynamics

We consider the following discrete time model of an energy storage unit (that can represent a battery, for example).

$$\begin{gathered} b(t) = b(t-1) - r(t) - b^{loss} \qquad \forall t \\ -r_{rated} \le r(t) \le r_{rated} \qquad \forall t \\ 0 \le b(t) \le B \qquad \forall t \end{gathered} \tag{1}$$

with given initial energy level $b(0) \geq 0$. We denote by $b(t)$ the level of the energy stored at time t (divided by ΔT) and by $r(t)$ the power exchanged with the storing device at time t. The b^{loss} term denotes a constant stored energy degradation in the sampling interval. Note that the power exchanged at time t, $r(t)$, can either be negative (the storage unit is charging) or positive (the storage unit is discharging).

A bus that does not include a storage device has

$$B_i = 0 \qquad i \notin \mathcal{B}. \tag{2}$$

The cost function for the storage units depends only on the actual capacity of storage:

$$C^b(t) = c^b(B - b(t)) \qquad \forall t \tag{3}$$

where c^b imposes a penalty proportional to the deviation of the stored energy level from the unit capacity, Atwa and El-Saadany (2010); Gayme and Topcu (2011).

3.2 Buses

We consider that each bus may have either generators or loads, or neither, or one of them. Further, except for the PCC, the following physical constraints need to be satisfied:

$$V_{\min} \leq V(t) \leq V_{\max} \qquad \forall t \tag{4a}$$
$$\theta_{\min} \leq \theta(t) \leq \theta_{\max} \qquad \forall t. \tag{4b}$$

Indeed the slack bus complex voltage is given as a reference and it is modelled as an uncontrollable source

$$V_{\min} = V_{\max} = V_0 \tag{5a}$$
$$\theta_{\min} = \theta_{\max} = 0 \tag{5b}$$

where V_0 is the PCC voltage magnitude given as a network parameter.

3.3 Generators

A generator is modelled as a controllable complex power injection at a specific bus

$$\tilde{S}^g(t) = P^g(t) + jQ^g(t) \qquad \forall t \tag{6}$$

subject to the following lower and upper bounds:

$$P^g_{\min} \leq P^g(t) \leq P^g_{\max} \qquad \forall t \tag{7a}$$
$$Q^g_{\min} \leq Q^g(t) \leq Q^g_{\max} \qquad \forall t. \tag{7b}$$

We assume the following generation linear cost function:

$$C^g(t) = cP^g(t) \qquad \forall t. \tag{8}$$

Furthermore, not all buses have connected generators

$$P^g_{i,\min} = P^g_{i,\max} = 0 \qquad i \notin \mathcal{G} \tag{9a}$$
$$Q^g_{i,\min} = Q^g_{i,\max} = 0 \qquad i \notin \mathcal{G}. \tag{9b}$$

3.4 Interaction with the utility grid

When grid-connected, the microgrid can purchase and sell energy from/to the utility grid. We consider this feature by modelling the PCC discontinuous linear cost function

$$C_0(t) = c^p \max(0, P^g_0(t)) + c^s \min(0, P^g_0(t)) \qquad \forall t. \tag{10}$$

Furthermore we define the following negative lower bound on its injected active power

$$P^g_{0\,\min} \leq 0 \tag{11}$$

to take into account bidirectional power flows. In summary when the microgrid sells power to the utility grid P^g_0 is less than zero and C_0 gives a negative contribution to the OPF objective function; vice-versa, when the microgrid purchases power from the utility grid, the PCC behaves as a generator ($P^g_{0\,\min} \geq 0$ and C_0 gives a positive contribution).

3.5 Loads and Renewable Energy Sources

Loads and renewable energy resources are uncontrollable quantity because they do not depend on the optimization variables. Therefore, they are represented at each time by fixed real and reactive power values (consumed/delivered) at the bus, and they give a negative/positive contribute to the power balance equations

$$\tilde{S}^d(t) = P^d(t) + jQ^d(t) \qquad \forall t \tag{12a}$$
$$\tilde{S}^{res}(t) = P^{res}(t) + jQ^{res}(t) \qquad \forall t. \tag{12b}$$

Note that demand and renewable unit profiles are time-varying and the network needs a forecast on the future loads and renewable power supply. There exist several mathematical models that allow us to forecast the renewable power distribution in time, e.g. solar irradiance, wind speed and biomass modelling, Atwa and El-Saadany (2010) and Atwa et al. (2010).

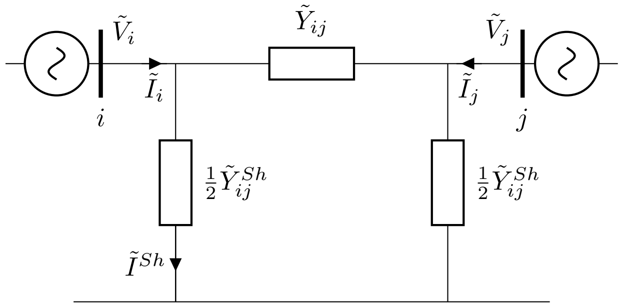


Fig. 1. π-model of a power transmission line.

3.6 Transmission lines

We use the well known π equivalent circuit in Fig. 1 to model the transmission lines Toro (1992).

The circuit current-voltage relation is given by the Kirchhoff 's equation,

$$\begin{bmatrix}\tilde{I}_i\\ \tilde{I}_j\end{bmatrix} = \begin{bmatrix}\tilde{Y}_{ff} & \tilde{Y}_{ft}\\ \tilde{Y}_{tf} & \tilde{Y}_{tt}\end{bmatrix}\begin{bmatrix}\tilde{V}_i\\ \tilde{V}_j\end{bmatrix} \tag{13}$$

where $\tilde{I}$ and $\tilde{V}$ are the current and voltage phasors and

$$\tilde{Y}_{ff} = \tilde{Y}_{tt} = \tilde{Y}_{ij} + \frac{1}{2}\tilde{Y}^{Sh}_{ij} \tag{14a}$$
$$\tilde{Y}_{ft} = \tilde{Y}_{tf} = -\tilde{Y}_{ij}. \tag{14b}$$

The complex power, injected at node i through the transmission line ij, is:

$$\tilde{S}_{ij} = \tilde{V}_i\tilde{I}^*_i = \tilde{V}_i(\tilde{Y}_{ff}\tilde{V}_i + \tilde{Y}_{ft}\tilde{V}_j)^*. \tag{15}$$

Therefore active and reactive power flow, on a line ij are written as non-linear functions of the i's and j's complex bus voltage

$$P_{ij}(t) = V_i(t)^2(G_{ij} + \frac{1}{2}G^{Sh}_{ij}) - V_i(t)V_j(t)G_{ij}\cos(\theta_{ij}(t)) - V_i(t)V_j(t)B_{ij}\sin(\theta_{ij}(t)) \quad \forall i,j,t \tag{16a}$$

$$Q_{ij}(t) = -V_i(t)^2(B_{ij} + \frac{1}{2}B^{Sh}_{ij}) - V_i(t)V_j(t)G_{ij}\sin(\theta_{ij}(t)) + V_i(t)V_j(t)B_{ij}\cos(\theta_{ij}(t)) \quad \forall i,j,t \tag{16b}$$

where $\theta_{ij} = \theta_i - \theta_j$.

Furthermore, for each transmission line we have a maximum apparent power $S_{ij\,\max}$, which give the following upper bound

$$|\tilde{S}_{ij}(t)|^2 = P_{ij}(t)^2 + Q_{ij}(t)^2 \leq S^2_{ij\,\max}. \tag{17}$$

At each time the nodal bus injections have to match the injections from loads and generators to have the power system balance. In the traditional ACOPF, this is expressed by active and reactive power balance functions of bus voltages and generator injections. That is

$$P_i^g(t) + P_i^{res}(t) - P_i^d(t) - \sum_j P_{ij}(t) + r_i(t) = 0 \;\forall i, t \tag{18a}$$

$$Q_i^g(t) + Q_i^{res}(t) - Q_i^d(t) - \sum_j Q_{ij}(t) = 0 \;\forall i, t. \tag{18b}$$

The model takes into account the power losses on the AC transmission lines, and if we consider the sum of (18a) on the entire network we obtain

$$\sum_{i=1}^{n} P_i^g + \sum_{i=1}^{n} P_i^{res} + \sum_{i=1}^{n} r_i(t) = \sum_{i=1}^{n} P_i^d + P^{loss} \tag{19}$$

The same happens for the reactive power (18b).

3.7 The Optimization Problem

The ACOPF optimal operational schedule consists in taking decisions on how much generators and storage units must produce to cover the entire network load while satisfying physical bounds, minimizing the cost function on generators, storage level, and the power exchanged with the utility grid.

Combining the expressions above, the OPF formulation with storage dynamics is:

$$\min_{\mathcal{X}} \sum_{t=1}^{T}\sum_{i=1}^{n} C_i^g(t) + \sum_{i\in\mathcal{B}} C_i^b(t) + C_0(t) \tag{20}$$

$$\text{s.t. } P_{ij}(t) = V_i(t)^2(G_{ij} + \frac{1}{2}G_{ij}^{Sh}) - V_i(t)V_j(t)G_{ij}\cos(\theta_{ij}(t)) - V_i(t)V_j(t)B_{ij}\sin(\theta_{ij}(t)) \;\forall i, j, t \tag{21}$$

$$Q_{ij}(t) = -V_i(t)^2(B_{ij} + \frac{1}{2}B_{ij}^{Sh}) - V_i(t)V_j(t)G_{ij}\sin(\theta_{ij}(t)) + V_i(t)V_j(t)B_{ij}\cos(\theta_{ij}(t)) \;\forall i, j, t \tag{22}$$

$$P_{ij}(t)^2 + Q_{ij}(t)^2 \le S_{ij\ \max}^2 \tag{23}$$

$$P_i^g(t) + P_i^{res}(t) - P_i^d(t) - \sum_j P_{ij}(t) + r_i(t) = 0 \;\forall i, t \tag{24}$$

$$Q_i^g(t) + Q_i^{res}(t) - Q_i^d(t) - \sum_j Q_{ij}(t) = 0 \;\forall i, t \tag{25}$$

$$P_{\min}^g \le P_i^g(t) \le P_{\max}^g \quad \forall i, t \tag{26}$$

$$Q_{\min}^g \le Q_i^g(t) \le Q_{\max}^g \quad \forall i, t \tag{27}$$

$$P_{i,\min}^g = P_{i,\max}^g = 0 \quad i \notin \mathcal{G} \tag{28}$$

$$Q_{i,\min}^g = Q_{i,\max}^g = 0 \quad i \notin \mathcal{G} \tag{29}$$

$$b_i(t) = b_i(t-1) - r_i(t) - b_i^{loss} \quad \forall i, t \tag{30}$$

$$-r_{rated} \le r_i(t) \le r_{rated} \quad \forall i, t \tag{31}$$

$$0 \le b_i(t) \le B_i \quad \forall i, t \tag{32}$$

$$B_i = 0 \;\; b_i^{loss} = 0 \quad i \notin \mathcal{B} \tag{33}$$

$$V_{i\ \min} \le V_i(t) \le V_{i\ \max} \quad \forall i, t \tag{34}$$

$$\theta_{\min} \le \theta_{ij}(t) \le \theta_{\max} \quad \forall i, j, t \tag{35}$$

$$V_{0\ \min} = V_{0\ \max} = V_0 \tag{36}$$

$$\theta_{0\ \min} = \theta_{0\ \max} = 0 \tag{37}$$

$$P_{0\ \min}^g \le 0 \tag{38}$$

where $\mathcal{X} = \{P_i^g, Q_i^g, V_i, \theta_i, r_i, b_i\}$ is the set of optimization variables. Next section illustrates simulation based results obtained by the solution of this problem for a Case Study.

4. SIMULATION RESULTS

The ACOPF problem (20)-(38) is a non-convex optimization problem whose objective function has discontinuous first order derivatives and we solve it through Interior Point OPtimizer solver (IPOPT) Ye (2011) in GAMS environment.

4.1 Case Study

The OPF formulation with storage dynamics (20) is implemented for a case study within the I3RES project [1]. The network, shown in Fig. 2, represents the feeder supplying some residential loads in Steinkjer, Norway. Currently the network consists of: a hydro power plants with 2 generators, 32 loads, 49 link buses (i.e. without generation nor load) and 84 transmission lines. In the future energy storage units and RESs may be included into the network.

The parameters and the boundary conditions associated with the generators and the PCC bus are given in Table 1. The cost of power purchased/sold from/to the main grid through the PCC can be found in Norway (2013), where the linear cost coefficient c^b for the storage unit is equal to 0.1 \$/MWh. The voltage magnitude limits for all buses are set to $0.95 \le V_i \le 1.05$ pu and the phase shift between the connected buses is set to 10°. Each transmission line has a maximum apparent power $S_{ij\ \max} = 7.2$ MVA. The storage is limited by a capacity B of 4 MWh with the maximal charge/discharge power rate r_{rated} equal to 1 MW and a storage energy loss b^{loss} of 0.01 MWh. The power profile generated by a wind farm depends on many factors, e.g. speed of wind, weather, number of wind turbines, and it has been considered as given in Chen et al. (2013). A sampling time of one hour has been chosen and the simulations have been performed over one day.

The simulation results illustrate the advantages of including an energy storage under a stressed load demand. During low demand, the energy is stored in the storage unit and then released when the load/demand is high, smoothing the total power injected into the grid. The progress of the reactive power is neglected since it does not contribute to the function cost.

4.2 Network behaviour under stressed load

The simulation has been performed using data from the stressed network situation on the 22th January 2013.

Note that when the storage unit is not considered into the network (see Fig. 3), the active power injected by the two

[1] www.demosteinkjer.no, www.i3res.eu

Table 1. Case Study: generation unit parameters.

Unit	$S_{\min}$ [MVA]	$S_{\max}$ [MVA]	c^g [\$/MWh]	c^s [\$/MWh]	c^p [\$/MWh]
Hydro$_1$	0	1.6	20	0	0
Hydro$_2$	0	1.0	20	0	0
PCC	0	4	0	30	160

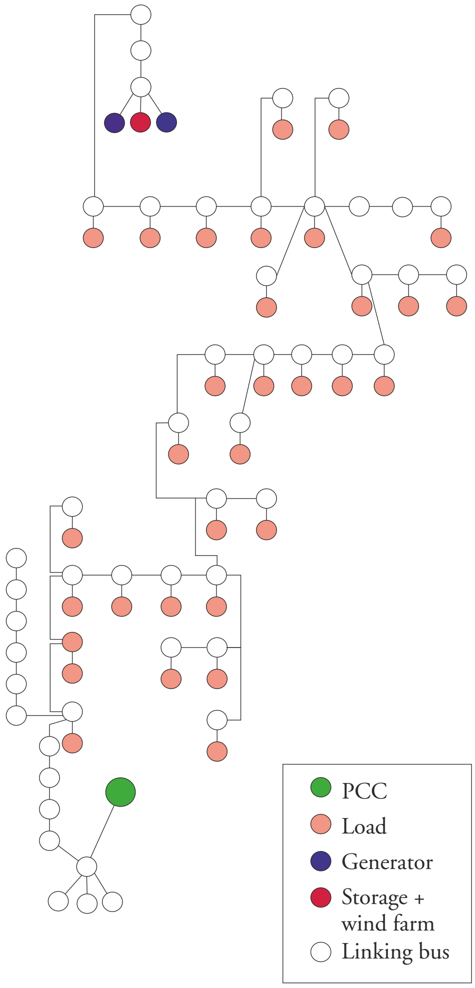


Fig. 2. Case Study: Demo Steinkjer network topology.

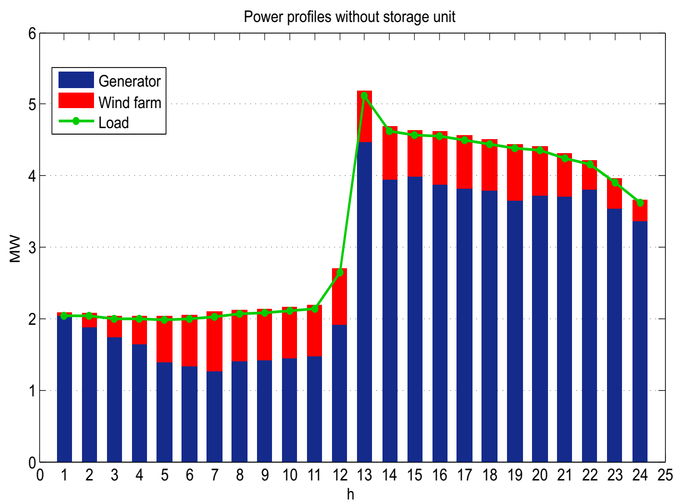


Fig. 3. Case Study: active power hourly evolution without storage.

hydro power units is equal to the active power loads minus the power injected by the RESs. The cost function value is 3192\$. Fig. 4 and Fig. 5 shows the advantages of using the reservoir storage: the storage unit avoids peaks (from $1pm$ to $12pm$) by reducing the cost value to 2726\$, that is a reduction of 14.6%.

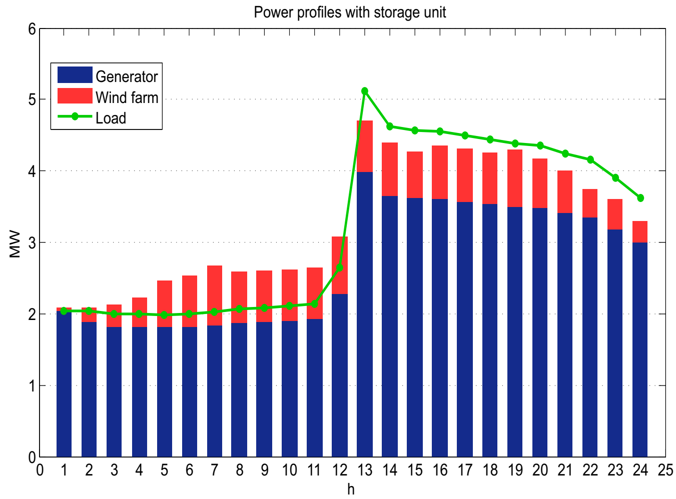


Fig. 4. Case Study: active power hourly evolution with storage.

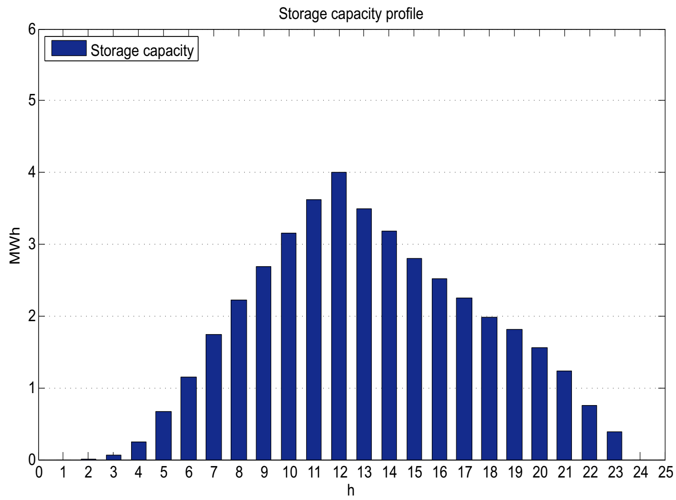


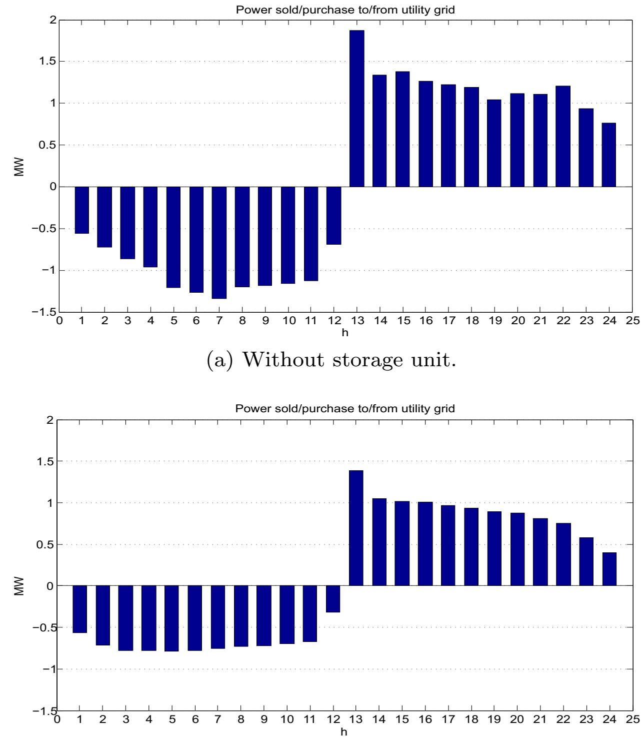
Fig. 5. Case Study: storage active power capacity trend.

If the power demand (including losses) is low enough, the hydro units can sell the surplus to the utility grid (see Fig. 6, from $1am$ to $12am$); otherwise the network needs to purchase power from it (from $1pm$ to $12pm$). Comparing Fig. 6a and Fig. 6b, it is worth noting that the optimal control leads a power purchase reduction from the utility grid in the hours when the generator can not provide the power required by the network. When a no stressed load profile is considered the advantages of the energy storage unit presence may be diminished.

The amount of time it takes to run a simulation depends on many factors, including the network's complexity and the computer's clock speed . We tested the OPF formulations and algorithm on a PC with Intel 3.12 GHz i7 processor, 12 GB memory. The simulation time of case study is 503 s without storage unit and 578 s including storage equations in the model.

5. CONCLUSION

This paper presents interesting results highlighting the benefits obtained by extending the traditional optimal power flow problem with an energy storage device. This is



(a) Without storage unit.

(b) With storage unit.

Fig. 6. Case Study: active power exchanged with the utility grid through the PCC bus.

quite relevant, particularly when renewable energy sources are integrated into the existing distribution/transmission grid, because their intermittent production affects negatively the energy balance in the grid. Energy storage units may be installed to mitigate this generation irregularity. However, the traditional tools/algorithms implemented to optimally balance the power flow in the grid do not consider explicitly storage units. The results have been obtained by simulating a real network in a real situation of load and they confirm the benefits of having a 'storage-aware' OPF algorithm, which in practice yields economical benefits.

Further work will be addressed to investigate different scenarios and optimization algorithms.

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