INTEGRATION OF PROCESS-SIDE ENERGY STORAGE AND ACTIVE DISTRIBUTION NETWORKS: TECHNICAL AND ECONOMICAL OPTIMISATION

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ABSTRACT

This paper is primarily aimed at demonstrating how energy tariffs with a significant price difference between day and night can make energy storage systems more profitable for an active customer. An optimisation procedure, based on the “energy hub” concept, has been devised and applied for a coordinated operation of local generation and process-side electric and thermal storages. The optimized integrated management of these systems enables an efficient use of primary sources, largely resorting to co-generation (CHP) and an optimal use of production and storage devices. Different case studies show how supply and distribution tariffs can influence the cost-effective operation of a CHP system, assuming the presence of various kinds of process-side storages.

INTRODUCTION

Electricity is a very special good: it can be very hardly stored and it needs to be generated at exactly the same time it is consumed. This requires a continuous control of the power system, for ensuring the on-line balance between generation and demand. Usually the energy demand is regarded as possible to be forecasted but not to be controlled, while generators have to follow the load profile, although working at low efficient operating points.

Recent developments in the generation scenario and the need for a higher level of power quality, as well as the possibility of exploiting renewable energy sources and co-generation, are strongly pushing forward the amount of generation directly connected to the distribution level. A continuously increasing share of this Distributed Generation (DG) has a stochastic behaviour, thus increasing the need for regulation and reserve margins.

The use of various forms of storage facilities eases the operation of the power system. Pumping storage plants, for instance, are being used for “peak shaving” and “valley filling” in the bulk power system. At the distribution level, balancing has never been a real issue; in fact the upstream transmission system has always been considered as an “infinite bus” able to balance the load and distributed generation fluctuations, then resulting in an implicit storage resource.

Energy storage opportunities on the process-side have rarely been exploited, although several processes have significant energy and/or mass storage, the larger usually being thermal and potential energy.

Today, the resort to energy storage systems for coping with the issues posed by the new grid paradigm and for really exploiting the possibilities offered by a large diffusion of distributed generation has become unavoidable. But, due to the relatively large cost of the most commonly used storage systems, a really effective solution must not only exploit grid-side resources, but also the demand side potential.

The paper applies the “energy hub” concept [1, 2] for a coordinated operation of local generation, process-side storages and final-use energy systems. Strategies for the integrated management of these systems are proposed to achieve an efficient use of primary sources and the optimal operation of production and storage devices. The effective management of the distribution system (quality of supply, power flows, energy losses) and the increase of the feasible DG share are other important issues which can be suitably improved by the widespread use of storage systems, but, for the sake of clarity, they are not treated in this paper.

Well-calibrated energy tariffs can induce positive behaviours in active and passive customers, because they can provide economic signals which stimulate power profiles consistent with a rational use of the energy grid resources. Moreover, the price difference between day and night can significantly affect the cost-effectiveness of a storage system, whose presence can reduce the peak demand, or at least shift it to off-peak hours.

ENERGY HUB MODEL AND OPTIMIZATION STRATEGIES

The energy hub is an interface between different types of energy vectors, aimed at efficiently transferring multiple energy flow. The matrix equation

\[
L - [C - S] \begin{bmatrix} P \\ \dot{E} \end{bmatrix} - P_{gen} = 0
\]

(1)

describes the relationship among output and input energy carries, where:

- \(L\) and \(P\) are power vectors of output and input ports respectively (active and reactive electric power, thermal load, gas, etc...);
- \(P_{gen}\) is the power vector of local generation at load side of the energy hub;
- \(\dot{E}\) is the vector of storage energy derivatives;
- \(C\) is the coupling matrix and its coefficients represent the relationship between each pair of energy carriers. They consider both the conversion efficiency of the converters depending on the converted power and the internal...
partition of an input energy carrier into several converters each;
S is the storage matrix and its coefficients represent how much the power exchanged with the system affects the stored energy.
Further details on the energy hub model can be found in [1] and [2].

**Figure 1 - Energy hub**

Typical elements composing an energy hub are power electronic converters, gas (micro)turbines, fuel cells, heat exchangers, batteries, gas tanks, etc, as schematically represented in Figure 1. In this work, in particular, a combined heat and power generator (CHP) and a furnace have been considered complemented by a thermal and an electrical storage device.

When suitably managed, the storages can be used to maximize the power production in CHP plants (and tri-generation plants) when power price is high and they can also be used to minimize the use of plants with higher operational costs, since storage devices can store the produced energy during cheap periods and release the stored energy during expensive periods [3].

Equation (1) is a non-linear constraint of the optimization problem that has been implemented to investigate the storage devices behaviour in a generation, conversion and storage centre. For the sake of clarity, in this work any generation and control of reactive electrical power on the output port have been neglected.

The optimization problem is to minimize the following objective cost function over 24 hours:

$$ C = f(E_{el}, P_{el}, mc_{gas}) + f_{sto}(E) $$

The term $f(E_{el}, P_{el}, mc_{gas})$ is the cost of the total daily input power. It is based on the tariff system applied (described below) and is given by:

$$ f(E_{el}, P_{el}, mc_{gas}) = \sum_{i=1}^{24} (\text{C}^{\text{imp}}_{i,el} E_{i,el}^{\text{imp}} + \text{C}^{\text{exp}}_{i,el} E_{i,el}^{\text{exp}}) + c_{el} P_{el}^{\text{max}} + \text{C}^{\text{fix}}_{el} + \sum_{i=1}^{24} (c_{i,\text{gas}} mc_{gas} + c_{\text{gas}} mc_{gas}^{\text{imp}} + c_{\text{gas}} mc_{gas}^{\text{exp}} + c_{\text{gas}} mc_{gas}^{\text{fix}}) $$

where:

- $c^{\text{imp}}_{i,el}$ [€/MWh] and $c_{i,\text{gas}}$ [€/m$^3$] are imported electrical energy and natural gas flow costs;
- $c^{\exp}_{i,el}$ [€/MWh] is the exported electrical energy cost;
- $c_{el}^p$ [€/kWp/day] is the electrical peak-power cost;
- $c_{\text{gas}}^{\text{fix}}$ [€/day/(m$^3$/day)] is the peak gas-flow cost;
- $c_{el}^{\text{fix}}$ [€/day] and $c_{\text{gas}}^{\text{fix}}$ [€/day] are electrical and natural gas fix costs;

$$ E_{i,el}^{\text{imp}}$$ [MWh] is the imported electrical energy;
$$ mc_{\text{gas}}$$ [m$^3$] is the imported gas natural flow;
$$ E_{i,el}^{\text{exp}}$$ [MWh] is the exported electrical energy;
$$ mc_{\text{gas}}^{\text{exp}}$$ [m$^3$] is the imported peak-flow;
$$ \max(P_{el})$$ [kW] is the peak-power.

The term $f_{sto}(E, P)$ in the objective function is the investment cost of storage devices, given by the fix value:

$$ f_{sto}(E) = \frac{k_{e} E_{\text{years}}}{365 \text{ years}} $$

where $E$ is the energy size of the storage (MWh), $P$ is its rated power (MW), $k_{el}$ and $k_{el}$ are appropriate cost coefficients and $\text{years}$ is the expected life time of the device; in this way, (4) represents the daily equivalent investment cost.

To be noted that in this optimization problem the size of each storage device is a problem variable, automatically set to the maximum value of stored energy reached during the period of time of the optimization. It is thus possible to assess the optimal size of storages, since their investment costs are part of the objective cost function.

**ENERGY TARIFFS**

Tariffs for energy transport and supply (particularly for electricity and gas) are an important tool that Regulators can use to induce power profiles coherent with a rational use of the energy grid resources [4].

For example, end-use tariffs not depending on the time of consumption do not provide any economic signal to stimulate a flat load profile or to encourage a peak-power reduction. In analogy, in the lack of electricity multiple tariffs with a significantly variable rate, usually a CHP plant will follow the thermal load profile, while using the electric system as an implicit and improper storage of huge capacity; in fact, the power grid is able to accept the exceeding electric generation, as well as to provide the lacking energy and just the tariff leverage can mitigate this behaviour.

Furthermore, multiple tariffs with substantial rate difference between day and night can make the end-use energy storage systems more cost-effective for an active customer. Since electric networks are sized on the peak-power demand, transmission and distribution companies are particularly interested to the techniques of Demand Side Response, in particularly the ones allowed by the
recent introduction of variable-rate electronic meters. Hence transport tariffs, set by such companies or by electricity Regulators, represent a primary instrument to make the customer power profiles more flat, or at least to shift their maximum consumption to off-peak hours. For what concerns the supply tariffs, in a deregulated market the hourly price of electricity is set by a Power Exchange or by bilateral contracts, then it cannot be managed by the Regulator. Anyway, the Energy Authorities usually continue to set the supply tariffs for ineligible customers and for the service of “last resort”. Then our simulations have assumed that the entire electric tariff can be manipulated by a Regulator. Under the base case scenario, the electricity and gas tariffs have been calibrated on the Italian situation (medium voltage/pressure client). In particular:

- the tariff for selling exceeding generation to the grid is proportional to energy volume [€/MWh], invariable along the 24 hours;
- the tariff for consuming gas is constituted by a fix term [€/year], a peak-flow term [€/year/(m³/day)] and a term proportional to gas volume [€/m³], invariable along the 24 hours;
- the tariff for consuming electricity is constituted by a fix term [€/year], a peak-power term [€/kW/month] and a term proportional to energy consumption [€/MWh], fairly dependent on the time of consumption (F1=“peak”, F2=“off-peak” and F3=“shoulder” time slot).

While the base case represents the present Italian tariff, three different scenarios (A, B and C) have been proposed to analyse the impact of regulation on the cost-effectiveness of end-use energy storages:

- in A, B and C, the price of purchased electricity is more and more differentiated between day and night, multiplying the F1 price by a term k and consequently reducing F2 and F3 to impose the invariance of the average electricity price for the reference load profile.
- in all scenarios, in order to penalize the day/night modulation of gas flow, a further term 0.04 €/m³/(PF-1) is added to fuel tariff, where the peak factor PF is the ratio between peak and average gas flow.

**CASE STUDIES**

An active energy consumer has been considered, characterized by the electric and thermal daily load curves reported in Fig. 2, provided with a 1.2 MW CHP generator, furnace and both electric and thermal storages. As discussed above, the tariff for selling exceeding generation to the grid is assumed to be 90 €/MWh from 8 AM to 8 PM, otherwise 45 €/MWh. The tariff for consuming gas is assumed to be 1850 €/year, 2.96 €/year/(m³/day) and 0.358 €/m³. The tariff for consuming electricity is 1218 €/year and 2.58 €/kW/month, plus the term proportional to energy consumption [€/MWh] shown in Table I.

Table II reports the main technical and economical results of the simulations. Three cases have been considered for each scenario: without storages (WS), with electrical storage (EI), with both electrical and thermal storages (EI+Eth). The costs are reported in €/day: the Total Cost is given by the Operational Cost plus the storage investment, spread over a 10 years lifetime period. The maximum stored energy, corresponding to the adopted storage size resulting from the optimization, and the daily Exported electricity are expressed in pu (Base Power = 1 MW). PBT is the Pay Back Time period of the storage devices, resulting from their investment costs and the expense savings they make possible in CHP operation. From Table II it may be observed:

- Electrical storage alone results convenient only with the tariffs with a higher day/night price difference (B and C), although with scenario B the PBT is close to the device lifetime (assumed 10 years).
- Combination of electrical and thermal storage is cost-effective in all cases, with interesting PBTs only with tariff scenarios B and C.

**Table I - Electricity purchase price (€/MWh)**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>k</th>
<th>F1 (Peak) h. 8-19</th>
<th>F2 (Off-peak) h. 7-8,19-23</th>
<th>F3 (Shoulder) h. 0-7,23-24</th>
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<tbody>
<tr>
<td>Base case</td>
<td>1</td>
<td>152</td>
<td>0</td>
<td>262</td>
</tr>
<tr>
<td>A</td>
<td>1.33</td>
<td>202</td>
<td>126</td>
<td>24</td>
</tr>
<tr>
<td>B</td>
<td>1.66</td>
<td>252</td>
<td>91</td>
<td>0</td>
</tr>
<tr>
<td>C</td>
<td>2</td>
<td>304</td>
<td>48</td>
<td>0</td>
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**Table II - Main technical-economical results**

<table>
<thead>
<tr>
<th>Storage</th>
<th>Oper. Cost</th>
<th>Total Cost</th>
<th>Max stored E_El</th>
<th>Max stored E_Th</th>
<th>Exported electricity</th>
<th>PBT [y]</th>
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</thead>
<tbody>
<tr>
<td>Tariff scenario: Base case</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WS</td>
<td>2835</td>
<td>2835</td>
<td>--</td>
<td>--</td>
<td>0.17</td>
<td>--</td>
</tr>
<tr>
<td>EI</td>
<td>2835</td>
<td>2835</td>
<td>0</td>
<td>0.17</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>EI+Eth</td>
<td>2781</td>
<td>2824</td>
<td>0.2</td>
<td>0.85</td>
<td>1.77</td>
<td>9.3</td>
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<tr>
<td>Tariff scenario: A</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WS</td>
<td>2855</td>
<td>2855</td>
<td>--</td>
<td>0</td>
<td>0.17</td>
<td>--</td>
</tr>
<tr>
<td>EI</td>
<td>2855</td>
<td>2855</td>
<td>--</td>
<td>0.93</td>
<td>--</td>
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</tr>
<tr>
<td>EI+Eth</td>
<td>2716</td>
<td>2845</td>
<td>0.92</td>
<td>1.77</td>
<td>2.47</td>
<td>9.3</td>
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<tr>
<td>Tariff scenario: B</td>
<td></td>
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<td></td>
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<td></td>
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<tr>
<td>WS</td>
<td>2662</td>
<td>2662</td>
<td>--</td>
<td>--</td>
<td>0.17</td>
<td>--</td>
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<tr>
<td>EI</td>
<td>2473</td>
<td>2643</td>
<td>1.54</td>
<td>--</td>
<td>0.09</td>
<td>9</td>
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<tr>
<td>EI+Eth</td>
<td>2444</td>
<td>2591</td>
<td>1.09</td>
<td>2.11</td>
<td>3.8</td>
<td>6.8</td>
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<td>Tariff scenario: C</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WS</td>
<td>2547</td>
<td>2547</td>
<td>--</td>
<td>--</td>
<td>0.17</td>
<td>--</td>
</tr>
<tr>
<td>EI</td>
<td>2221</td>
<td>2409</td>
<td>1.75</td>
<td>--</td>
<td>0.03</td>
<td>5.8</td>
</tr>
<tr>
<td>EI+Eth</td>
<td>2241</td>
<td>2410</td>
<td>1.35</td>
<td>1.82</td>
<td>3.4</td>
<td>5.6</td>
</tr>
</tbody>
</table>
As expected, the presence of thermal storage significantly enhances the electrical energy exported to the network. The benefits of adopting tariffs with a higher day/night price difference may be better demonstrated by analysing the daily behaviour of the energy hub. As an example, Figs 3 and 4 report the multi-period (24 hours) optimal dispatch of the energy hub, equipped with both electrical and thermal storages for two tariff scenarios (Base case and B respectively). It can be noted that in the former case the CHP production (and thus the natural gas input) tends to follow closely the electric load curve, with little use of the storage devices. With the incentive tariff (Scenario B) the optimization procedure leads to a much greater exploitation of both electric and thermal storages, whose energies are suitably modulated resulting in a more uniform natural gas input and CHP production during the “peak” time period. It is also worth noting how the electric energy exchange with the grid is improved, with a greater import during the “off-peak” and “shoulder” periods and a significant export during the “peak” period (when the selling tariff is higher). This behaviour, besides lowering the overall operating costs for the consumer, results useful to the supply network, by reducing the daily peak demand.

CONCLUSIONS

A multi-period optimization procedure based on the energy hub concept is applied to optimize the efficient operation of a CHP plant with electric and thermal end-use storages, from the strict point of view of the active customer.

REFERENCES


