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Operation of a photovoltaic-wind plant with a hydro pumping-storage for electricity peak-shaving in an island context

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ABSTRACT

A simulation tool for the operation of a hybrid PV/Wind plant coupled with a hydro-pumping storage (HPS) was built; it was used for simulating the behavior of such a system among an energy mix constituted by fuel oil generators and electrical cables in an insular electrical network. Each subsystem is modeled with a variable efficiency depending on the operating regime and on solar and wind sources variability. An optimization of the hydro-pumping system operation was developed using four reversible pumps in parallel. The objective is to shave the electrical peak demand in replacement of costly and polluting combustible turbines. An energy situation like the one in Corsica Island is considered and all the electrical productions are taken into account, not only renewables but also fuel and imported electrical energy. The covered part of the peak demand can reach 80% in an annual basis and the influence of the hybrid system characteristics on the performances were studied. Some hybrid systems configurations were highlighted.

1. Introduction and brief literature review

The wind and PV energy are intermittent and stochastic: the energy producer doesn't control its production. It is a significant handicap because these sources may not produce when the electricity demand is high and can produce a disturbing excess energy when the consumption is low. Their potential is then reduced, particularly if no energy storage means are used; this excess renewable energy can be not accepted in the network and is lost (Dambrine et al., 2012).

The power generated by PV or wind energy (WE) systems must be limited to guaranty an electrical stability and a production/consumption balance. The high sensibility of grid connected Renewable Energy systems (RES) to an electrical perturbation often leads to a production disconnection when some incidents occur on the network. This disconnection increases the imbalance between production and consumption and the risk of major incidents. In Denmark, some feedbacks show that for a penetration rate up to 20–30% some stability problems occur (Robyns et al., 2006; Crappe, 2003). A French order of April 23, 2008 states that "any facility . . . implementing random energy can be disconnected . . . when the active power from these plants reached 30% of the total active power in the network" (Legislative decree, 2008). The same maximum penetration rate of RE systems is used in other locations as Canary Archipelago.

This problem has more serious consequences in islands (Notton, 2015); in not interconnected areas, almost always the case in insular context, the power balance between production and consumption is more difficult to maintain because only local energy production means are available. A lack of power cannot be compensated by mainland production means and an excess production cannot be evacuated toward a mainland electrical network. Moreover, in an island, the smallness of the territory complicates the utilization of intermittent RES, it reduces the aggregation effect (smoothing of the intermittent production due to the repartition of WE or PV systems spread over a large territory and subject to different weather conditions).

An energy storage system stores the energy generated during periods with low demand or high production and restitutes it at time of high demand and/or low production. Storage also allows:

- to delete or to smooth the peaks of energy consumption during the day;
- to prevent the fluctuations and the problem of frequency regulation.

With intermittent RE sources, it stores the electricity produced beyond the limit of 30% imposed by the French rules and restores it according to the needs and the operating strategy.

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The storage acts as a damper and regulator in the electric network, solving the fluctuation problems and improving the quality of distribution. An adapted storage allows to manage the energy flows among the RE generator, the energy storage and the grid. Storage means is usually classified into 3 categories (ESA, 2010; Butler et al., 2002):

- Bulk energy storage or energy management storage used to decouple the timing of generation and consumption.
- Distributed generation or bridging power, for peak shaving. Storage is used to assure continuity of service when switching from one energy source to another.
- Power quality or end-use reliability. Stored energy is only applied for seconds or less to assure continuity of quality power.

Not all technologies are suitable for all applications, due to limitation in power or storage capacity. Response time is another critical issue, particularly for power applications for which the system must be available rapidly (Schoenung and Hassenzahl, 2007; Rastler, 2009).

Here, a hydro-pumping system is used as storage, it responds quickly to a rapid power demand and is able to reach, in some seconds its nominal power (rapid ramp rate). In the World, more than 300 HPS are installed for a capacity of 127 GW, the usual HPS sizes are from 1 to 1.5 GW sometimes 2–3 GW and the energy storage can reach several GW h. The common size for turbines is 300–400 MW (Katsaprakakis et al., 2008; Gimeno-Gutierrez and Lacal-Arantegui, 2015) with an average efficiency around 80%. In the European Union, about 7400 MW of new HPS are planned for about 6 M$ (+20% of the installed capacity (Punys et al., 2013)).

HPS are characterized by (Singh et al., 2014; Ren et al., 2013):

- a storage capacity depending on the storable water quantity and on the difference in elevation between both tanks;
- a power reserve for storage and discharge depending on the capacity of pipes, turbines and pumps;
- a time constant: storable energy per power unit;
- an efficiency, ratio between electrical energy produced during turbine phase on that consumed during pumping phase.

More WE and PV systems are installed in a territory, more electricity is produced and of course the risk of power shortages is reduced, but at the same time the risk to produce too much energy (compared to the consumption) increases and induces the curtailment of WE and PV production (Hosseini-Firouz, 2013; Ummels et al., 2008; Rahimi et al., 2013). HPS is adapted for seasonal balance and improves the electricity distribution quality (Hedegaard and Meibom, 2012).

The association HPS/wind farms is competitive (Zafirakis et al., 2013; Connolly et al., 2012; Tuohy and O'Malley, 2011) for small electrical grid and island ones (Anagnostopoulos and Papantonis, 2008), particularly for Greek islands (Katsaprakakis et al., 2012; Kapsali et al., 2012; Kaldellis and Kavadias, 2001; Papaefthymiou et al., 2010; Anagnostopoulos and Papantonis, 2012). The introduction of a HPS into the Irish grid increased the WT integration rate and reduced the operation costs (Connolly et al., 2012). A well-known WT/HPS system has proved its effectiveness and it success in El Hierro Island (Canarian Archipelago) (Bueno and Carta, 2006).

The combination HPS/PV was less studied:

- sizing methods were developed (Kaldellis et al., 2009, 2010; Ma et al., 2015); in these methods, a constant efficiency for the pump/turbine group is considered independently of the operating regime;
- a PV/HPS system can provide a continuous energy (Margeta and Glasnovic, 2010, 2011);
- Ma et al. (2014a) studied a small autonomous PV/HPS plant for remote regions;

Using together wind and solar resources reduces the production variability (Hoicka and Rowlands, 2011). PV/WT/HPS systems were used for water desalinization (Kalogirou, 2005; Garcia, 2003; Spyrou and Anagnostopoulos, 2010). New strategies of development of such systems in optimizing the storage capacity and maximizing the profitability in a deregulated energy market were analyzed (Ardizzon et al., 2014).

An optimization of a PV/WE/HPS system in autonomous mode showed that the HPS efficiency (Energy produced in turbine mode on energy used in pump mode) was 52.5% (Ma et al., 2014b). HPS are the best solution for smoothing the electrical production at the lowest cost (Papaefthymiou and Papathanassiou, 2014; Papaefthymiou et al., 2015; Santhosha et al., 2014; Muche, 2009; Malakar et al., 2014; Kanakasabapathy and Shanti Swarup, 2010). The imbalances due to wind variability is avoided by HPS (Castronuovo and Pecas Lopes, 2014) and the influence of prediction inaccuracies strongly reduced (Bayón et al., 2013).

Anagnostopoulos and Papantonis (2008) showed that a variable speed pump is more efficient than a constant speed pump and is a more profitable solution. In summary, this short literature review showed:

- HPS are the less expensive energy storage means with a good global efficiency;
- HPS provide a high flexibility for the electrical networks;
- HPS are particularly adapted for isolated grid;
- HPS reduce the lost renewable energy and increase the integration rate of intermittent RE.

In this work, a HPS, using reversible pumps, is coupled with PV and WE plants for covering periods of peak energy demand in replacement of costly combustion turbines using diesel or gas fuel. A simulation tool using hourly meteorological and load data, is developed for determining both energy and water flux taking place into the hybrid system. The energy intakes from conventional diesel engine plants and from two import electrical cables are also taken into account. A general description of the studied system is shown in Fig. 1.

The highlights of this work are:

- WE and PV production being intermittent, the operating conditions of the reversible pumps change; the pump efficiencies (in pump and turbine modes) are highly dependent on the received

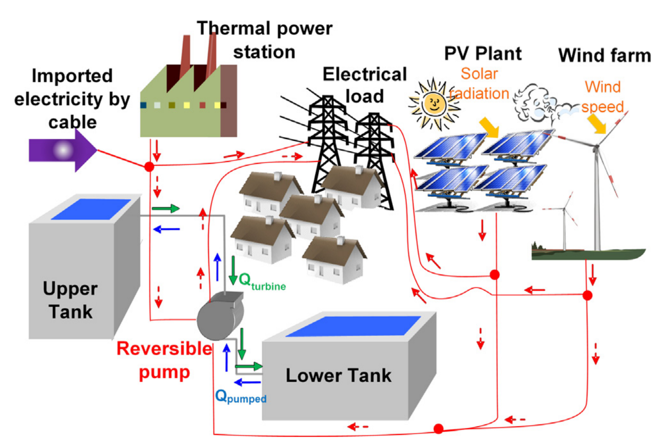

Fig. 1. General description of the studied system.