pImprovement of hydro pump storage flexibility to maximize the use of renewable energy sources

Anjan Kumar Sahoo
College of Engineering Bhubaneswar, Odisha, India

Keywords: Hydro pumping storage, Renewable Energy Sources, Ancillary Services, Power Dispatching.

Abstract

Sardinia is an excellent option for a test bed for smart grid development scenarios since it has a lot of potential for solar and wind power while having very little electrical infrastructure and limited connections to the mainland. In light of this, the research investigates the use of hydro pumping as a smart grid element that may be applied as a flexible storage compensator for solar and wind energy in the Sardinian power transmission system. The study investigates the greatest quantity of renewable energy that, by employing hydro pumping storage technologies in a different way, might be incorporated into the Sardinian power system.

1 Introduction

Sardinia has geographical conditions that can be exploited for the production of energy from Renewable Energy Sources (RES), like wind and sun, and for that reason in the last years experienced a great increment of renewable power generation. Considering the power generation facilities in the year 2012 the total energy production was 13,346.9 GWh, exceeding the demand, which was 10,998.8 GWh, by 21.3% [1]. Yearly power production divided by technology in 2013 is presented in Fig. 1, which shows that the RES share in the total electricity production is about 24.5%.
In this context, having in mind the need of further maximization of the exploitation of RES, in order to reach and overcome the EU 2020 climate and energy targets, which require raising the share of EU energy consumption produced from renewable resources to 20%, the paper investigates the use of hydro pumping storage (HPS) as a smart grid player to be used as flexible storage compensator for wind and solar generation in the Sardinian power transmission grid. Indeed, even though Sardinia had already reached the regional burden sharing mainly due to a regional demand reduction of 16.1% in 2013 [1], the available natural resources suggest a further increase of RES penetration that can be more easily accepted S ix of generation in the Sardinia power system, only partly alleviated by the novel HVDC connection with the mainland.

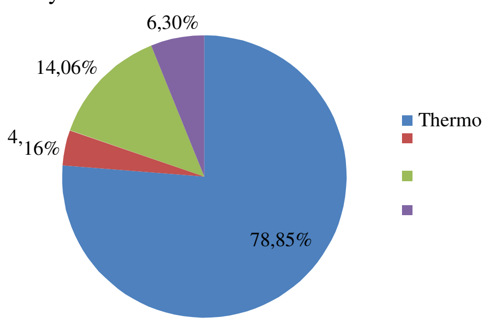

Fig. 1. Power supply in 2013 per production technology

Thus, The paper aims at showing at what extent HPS might be useful to integrate intermittent sources, such as wind and solar, by limiting the amount of renewable energy curtailments.

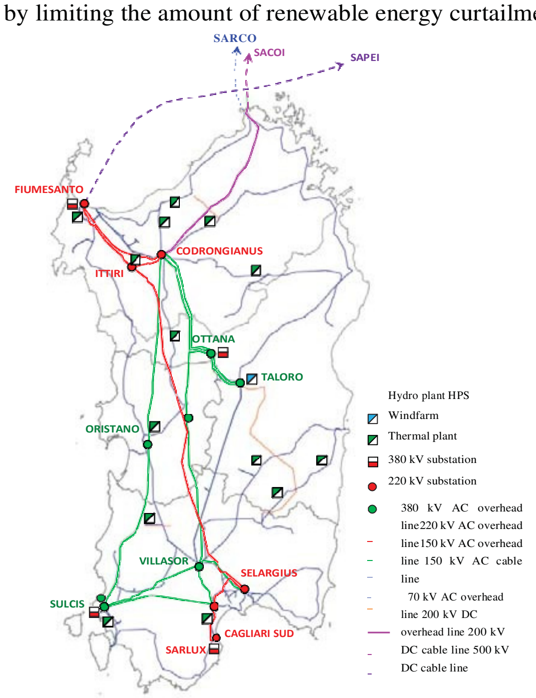

Fig. 2. A schematic view of the Sardinian power grid

2 Sardinian power system, generation and demand

The Sardinian power system can be described according to the picture shown in Fig. 2 that is related to 380-220-150 kV transmission systems.

Power Generation facilities

The Sardinian total generation capacity is about 4,900 MW, as summarized in Table I, subdivided by different generation technology. Table I also reports the expected new RES installation forecasted by the Energetic and Environmental Plan for Sardinian Region - PEARS for years 2014-2020 [2].

TABLE I. SARDINIAN GENERATION CAPACITY [MW]

Generation Technology	2013	2020
Thermal	2,822	2,822
Hydro	466	466
Wind	988	1,500
Photovoltaic	680	1,000
Total	**4,956**	**5,688**

Thermoelectric energy production in Sardinia is dominated by conventional coal and oil-fired plants of Fiumesanto, Sulcis, Ottana and Sarlux, which is an integrated gasification combined cycle plant (IGCC) that gasifies residual oil from the refinery processes to generate electricity.
Actually, the total Hydro generation capacity installed is 466 MW, with 240 MW allocated in the Taloro hydro-pumped plant, normally used for load balancing and for selling energy during peak hours when energy price is high.
The capacity of wind generation installed in Sardinia is 988 MW, with the most installed in the North of the island. Wind farm sizes range from 20 to 160 MW. The connection to the grid is usually to the 150 kV transmission network.
Finally, according to the statistics published by the Gestore Servizi Energetici (GSE) [3], which is the state-owned company that promotes and supports RES in Italy, the number of PV installations in Sardinia has reached in April 2014 a total capacity of 680 MW. The vast majority of PV plants are connected to medium and low voltage distribution networks.
The total photovoltaic generation in Tab. I is bigger than the data reported in [2], because concentrated solar power (CSP) and concentrated photovoltaic (CPV) have been added. Table I also includes the wind generation outlook for 2020 [2].
Finally, Biogas generation plants will be installed in Sardinia, but due to their small size, they are not considered to be relevant for this study.

2.1 Transmission System

The Sardinian transmission grid is approximately constituted by 4,000 km of lines, owned and managed by the Italian TSO TERNA. The power system comprises transmission lines at 380-220-150 kV. The 380 kV EHV transmission network from North to South of Sardinia connects the two areas with the biggest power plants. A short 380 kV EHV line connects the two HVDC stations existing in Sardinia. In fact, Sardinia is connected to Italian mainland through two HVDC submarine cables. The first one is called SA.CO.I. (SArdegna-COrsica-Italia), and has a transmission capacity of 300 MW. The second one, SA.PE.I. (SArdegna PEnisola Italiana), was built in 2011 and it has a 1000 MW capacity. Currently, both connections are prevalently used to export energy to the mainland.

Sardinian Load Demand

The consumption of electricity in Sardinia is registering continuous decrements, mainly due to the economic crisis and the closing of many industrial facilities.
The typical behaviour of the Sardinian demand is showed in Fig. 3 where there are two representative daily load curves, observed in January and June 2013 [1],[4].

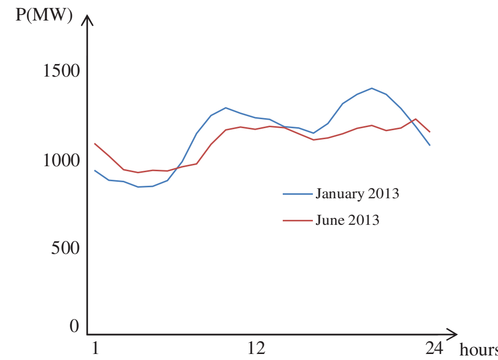

Fig. 3. Hourly demand for Sardinia in Januanry and June 2013

In 2013, according to the daily load duration curve (LDC) of the demand the highest peak load registered was 1,874 MW, whereas the lowest at off peak hours was 772 MW (Fig. 4).

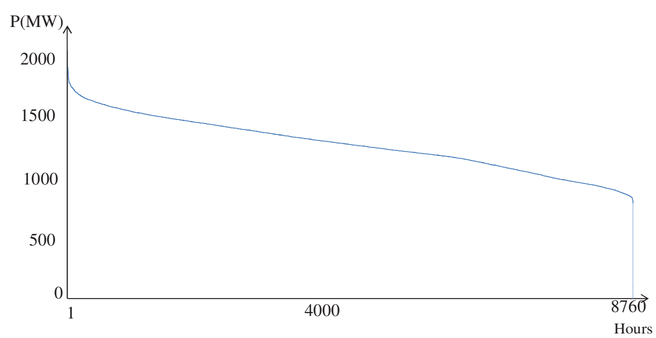

Fig. 4. Load duration curve of the demand in Sardinia - year 2013

2.3 Impact of RES on the Italian energy market

By considering the above figures, and taking into account that in 2013 the demand in Sardinia was about 1874 MW at peak hours and 722 MW at off peak hours, it is evident a prominent gap between generation capacity and demand. This gap has negatively impacted the price of energy in Sardinia and caused excessive costs for ancillary services, up to the year 2011, when the Sardinian power system is

Interconnected to the Italian mainland with the high voltage direct current (HVDC) connection SAPEI, which allows 1000 MW import/export with the mainland. The building of the SAPEI permitted overcoming the "isolated condition" for the Sardinian power system, giving the possibility to export the exceeding production, and allowing conventional generation plants to be dispatched according to wholesale power market prices. The getting into service of SAPEI resulted also in a reduction of energy prices in Sardinia. In fact, the SAPEI link, which allows large quantities of energy to be exchanged with the Italian mainland, makes the hourly energy price in Sardinia similar to the prices in north of Italy, where the power system is very well interconnected with the rest of Europe. This is also due to the Italian market scheme, where renewables sources have dispatching priority, and have to offer their energy as a price taker. That is, regardless of what the price is, RES will supply all the energy they can and will settle on whatever price the market dictates.

Definitely, during the day, due to the impact of RES on prices, the zonal prices in Sardinia are very low, frequently below 40 €/MWh, and in some case not sufficient to recover production costs.

For the above reasons, some thermoelectric plants in Sardinia, recognized as essential for grid security by the TSO, are committed and operated at minimum power and are obliged to participate to the market providing offers at defined power and for a specified time interval. Given that this way of operation is uneconomic some generation companies are compensated for this ancillary service.

3 Hydro pumping storage for RES exploitation

Variable speed pumped-storage plants are receiving much interest in academia and industry due the usefulness in the management of renewable energy intermittent and variable production. Sardinia is a suitable case study to demonstrate the potentialities of HPS. In fact, Sardinia has a relatively confined electricity grid with limited interconnections to the mainland and, on the other hand, has high solar and wind power potential, offering viable options as laboratory for the Smartgrid development. One possible implementation of Smartgrid concept could be to change the usual operation of the pumping storage in Sardinia. Indeed, large amounts of intermittent sources such as wind and solar may create operational problems requiring the intervention of the TSO to solve grid issues and for guarantee the security of the power system. For system operation with high RES production the following actions could be implemented by the TSO:

- generation curtailments during congestion events for security reason;
- management of surplus wind/solar generation during light load periods with power reduction of conventional generating units;
- commitment of expensive larger operating reserves (e.g. Gas Turbine Thermoelectric Plants).

In this context, the use of hydro pumping storage provides opportunity for better management the variable renewable energy resources, giving the possibility to implement Smartgrid operation procedures also with renewable energy, like energy time-shift, regulation, load following, and operational reserves.

Recently developed and projects under development in Europe and in Asia are summarized in Table II [7].

TABLE II. HPS PROJECT WORLDWIDE

HPS Plant	**Country**	**Size (MW)**	**Operation Start**
Yagisawa	Japan	85	1990
Takami	Japan	105	1993
Okawachi	Japan	790	1993
Shiobara	Japan	360	1995
Okukiyotsu	Japan	690	1996
Yanbaru	Japan	31,5	1999
Goldisthal	Germany	662	2003
Omarugawa 4	Japan	320	2007
Omarugawa 3		345	2009
Avče	Slovenia	195	2010
Omarugawa 2	Japan	345	2010
Omarugawa 1		320	2011
Kozjak	Slovenia	230	2012
Nante DeDrance	Switzerland	320	2015
Linthal 2015	Switzerland	1000	2015
Tehri	India	1224	2015
Vendanova III	Portugal	840	2015
Kühtai 2	Austria	1801	2015
Kyogoku	Japan	228	2015
Kühtai 2	Austria	180	2015
Kyogoku	Japan	228	2015
Kazunogawa	Japan	950	> 2017

With the development of new power electronic components, high power converters can be designed for innovative applications in HPS stations [8-10].

Paper [8] presents the 300 MW drive system consisting of a cyclo converter with Doubly-Fed Asynchronous Machine (DFAM) operating in the HPS plant of Gold is the 1 mentioned in Table II and shown in the configuration in Fig. 5 a.

The new voltage source converters topologies, based on back-to-back voltage source converters, are also becoming relevant for feeding the rotor windings of the DFAM according to configuration in Fig. 5 b [9,10], and are being used in some of the most recent pumped-storage implementations.

In this study, it is supposed to consider the Taloro plant equipped with an innovative variable speed motor/generator able to implement flexible power output adjustments, which are not possible in the pumping operation stage with conventional synchronous machines.

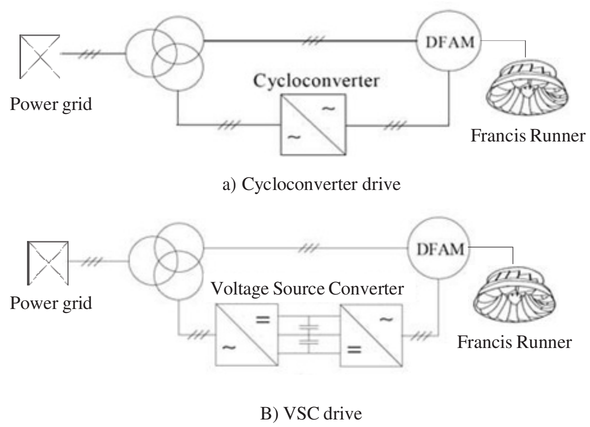

Fig. 5. Variable speed converters for HPS.

4 HPS in Sardinia: results and discussion

The impact of the smart flexible use of HPS in Sardinia is analysed considering the following scenarios.
In the first scenario, called S1, the generation installed in Sardinia is considered. The load flow is performed for 8760 hours, and critical situations are put into evidence. In the second scenario S2, the data in Table I are used for 2020 with the assumption that conventional HPS, based on the synchronous generator technology existing in Sardinia, will be used. Finally, in scenario S3, the 2020 scenario is considered under the hypothesis of variable speed pumping instead of the synchronous motor.
Sardinian power system is simulated under the hypothesis of considering a base-load of 1,200 MW, and taking into account the variability of Wind and PV energy production. Wind production has been simulated by using real wind speed time series measured in Sardinia. Photovoltaic production is simulated by means of true solar irradiation data [5].
Fig. 6 shows the chronological simulation for photovoltaic and wind energy production.

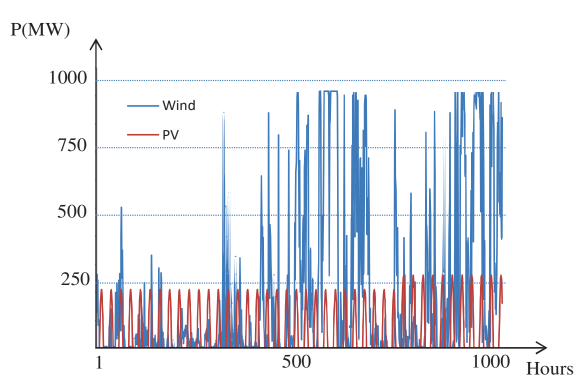

Fig. 6. Hourly Wind and Photovoltaic production simulation.

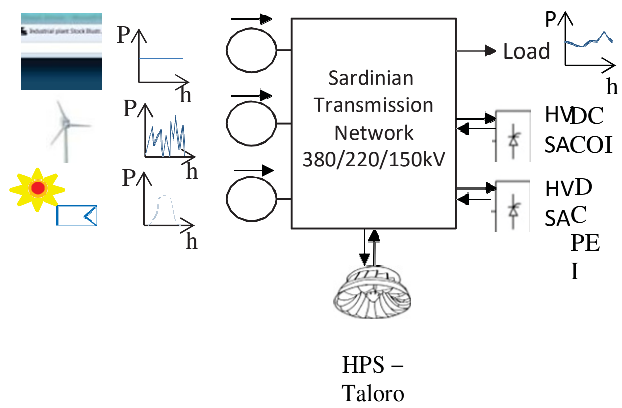

Fig. 7. Power system configuration for power flow studies.

Hourly load variation is simulated with the data provided by Terna [1] and GME [3].
MATPOWER has been used for solving power flow case studies [6], according to the configuration depicted in Fig. 7, where the generators are connected to bus nodes at the different voltage levels 150/220/380 kV. The load is aggregated in the HV/LV substation connected at HV level.
The HPS corresponds to Taloro power station, and it is committed to provide additional load at times of high RES generation and low electricity demand, enabling further RES peak capacity and/or regulating the export through HVDC connections SAPEI and SACOI.

4.1 2014 Scenario S1

Fig. 8 shows a chronological simulation of 1000 hours, emphasizing the variability of the power exported through SAPEI.

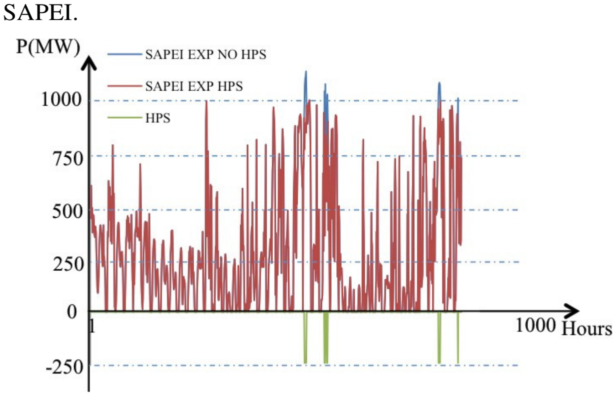

Fig. 8. SAPEI Export and HPS state – Scenario S1.

Actual generation production produces almost continuous SAPEI operation in export state. SACOI is used generally to export 50 MW to Corsica.
HPS is used when the production overcomes the SAPEI limit of 1000 MW, for 395 hours per year. Also with HPS usage the 1000 MW limit is still reached, and in this case it is necessary to use also the SACOI link or curtail wind production. This last option is generally avoided for not incurring in the compensation tariffs for wind curtailment.
The SAPEI loading is above 50% for more than 2000 hours per year (Fig. 9).

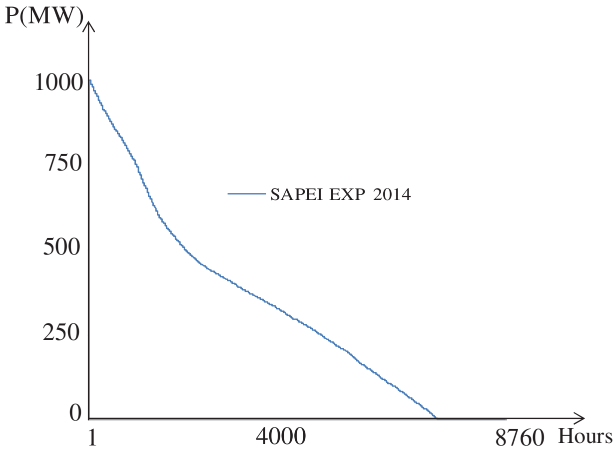

Fig. 9. SAPEI Export – Load duration curve Scenario S1.

2020 Scenario S2 – HPS with synchronous machine

Fig. 10 shows the comparison between the power exported through the SACOI and SAPEI link in 2020.
The approach followed in this simulation is to use SACOI only in the situations in which the generation is very high, whereas normally the SAPEI is used to export energy to the mainland. A fixed loading of 50 MW is considered as Corsica feeding.

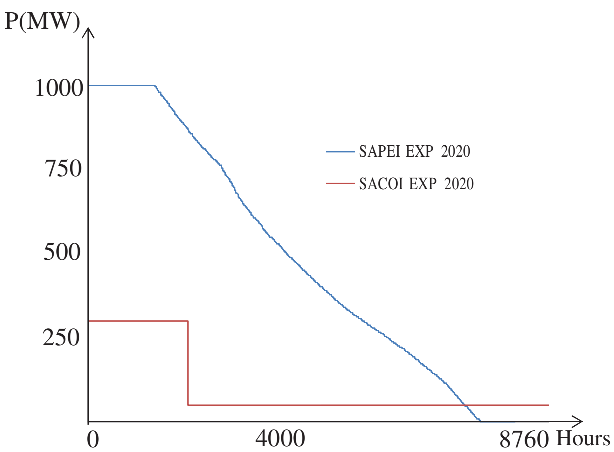

Fig. 10. SAPEI and SACOI Export – Scenario S2.

Fig. 11 shows the comparison between the LDC of the SAPEI loading in 2014 and in 2020. The energy exported grows from about 2,890 GWh to 4,079 GWh per year.
The HPS is committed for 1906 hours per year and the pumped energy is 457 GWh. In this condition the HPS is not used to solve all contingencies and wind power curtailment is necessary for 1267 hours per year, corresponding to 788 GWh of energy curtailed.

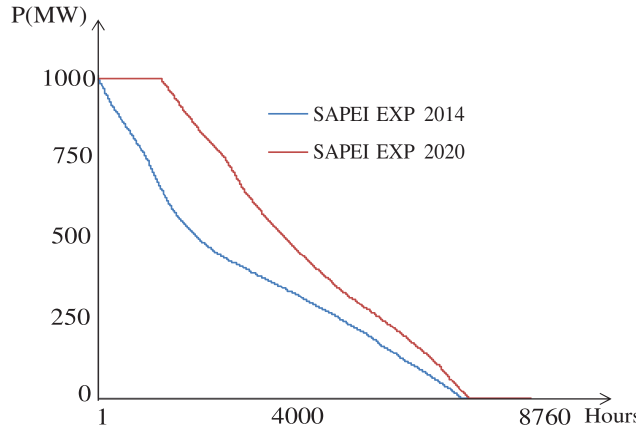

Fig. 11. SAPEI Export 2014 and 2020 – Scenario S2.

2020 Scenario S3 –HPD with variable speed machine

Unlike conventional hydro power plants, variable speed pumped-storage plants use asynchronous motor-generators that allow the pump turbine rotation speed to be adjusted. DFAM use also permits reducing the number of starts and stops in changing generation/pumping mode, helping to regulate the network frequency or voltage also in pumping mode, as well as operating closer to the turbines optimal efficiency point, which results in a significant increase of the global plant efficiency.
In this paper, the HPS is used in pumping mode, with variable output, in order to limit the pumping power only to maintain the power exchange in the SAPEI link at the nominal rating, and limiting the pumped energy.
Fig. 12 shows the comparison between the LDC of the SAPEI loading in 2020 with Taloro plant working according to existing infrastructure with synchronous generator/motor or assuming a revamping with variable speed machines.

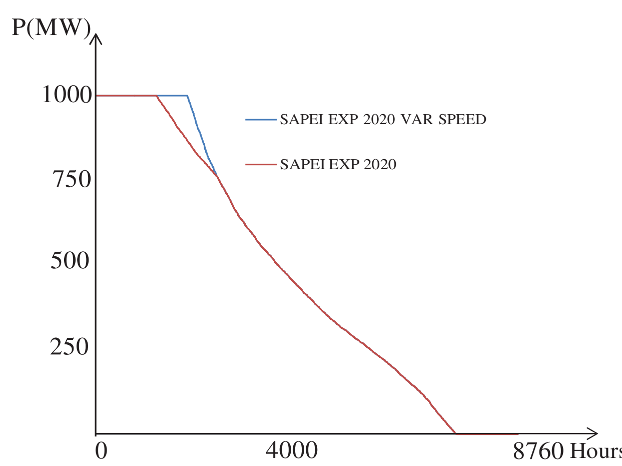

Fig. 12. SAPEI Export 2014 and 2020– Scenario S3.

The HPS is still committed for 1906 hours per year but the pumped energy, due the variable speed regulation, decreases

to 376 GWh, and the wind energy curtailed remains the same given that the curtailment acts only when no further chances to export energy exist.
The 100% of SAPEI loading increases from 1267 hours per year to 1907 hours per year.

Conclusions

Traditionally hydro pumping storage has been used in Sardinia for load balancing. Low-cost off-peak electric power was used to run the pumps, whereas during on-peak hours the stored water was released through turbines to produce electric power.
In this paper HPS is used as a flexible resource, that can be operated with the objective of compensating excessive wind and photovoltaic power production. The findings of this study may be useful as a starting point to consider new renewable energy policies and strategies for the expansion of RES installations at regional or national level. Sardinia is a good example of an experimental region where could be possible to achieve 100% RES electricity supply by applying pumped hydro and other storage technologies.

References

[1] Trasmission System Operator TERNA. Statistical Data. www.terna.it.
[2] Energy and Environmental Regional Plan - Sardinia Region. Piano Energetico ed Ambientale della Regione Sardegna-PEARS (in Italian). Available: www.regione.sardegna.it.
[3] State-owned company which promotes and supports RES in Italy. GSE (Gestore Servizi Energetici). www.gse.it.
[4] Energy Market Operator GME. Statistical Data. www.mercatoelettrico.org.
[5] E. Ghiani, F. Pilo, S. Cossu, Evaluation of photovoltaic installations performances in Sardinia. Energy Conversion Management, 76 (2013), pp. 1134–1142.
[6] R. D. Zimmerman, C. E. Murillo-Sánchez, and R. J. Thomas, "MATPOWER: Steady-State Operations, Planning and Analysis Tools for Power Systems Research and Education," Power Systems, IEEE Transactions on, vol. 26, no. 1, pp. 12-19, Feb. 2011.
[7] F. Duarte. Venda Nova III facing variable speed. Technical Hydropower Production Conference 2011 Oslo, 8 March 2011.
[8] A. Blocquel and J. Janning, "Analysis of a 300 MW variable speed drive for pump-storage plant applications," in Proc. EPE , Dresden, Germany, Sep. 2005.
[9] A. Hämmerli, B .Ødegård, "AC excitation with ANPC – ANPC converter technology tailored to the needs of AC excitation equipment for pump storage plants," ABB Review, No. 3, 2008, pp. 40-43
[10] Mitsubishi. "Pumped Storage Power Station with Adjustable Speed Pumped Storage Technology," Presentation available from TERIIN - The Energy and Resources Institute. Accessed June 2014, www.teriin.org.