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Extended summary

Artificial intelligence and new technologies for photovoltaic systems in the Italian scenario

Curriculum: Ingegneria Informatica, Gestionale e dell'Automazione

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Abstract. The rapid depletion of conventional energy sources and the ever-increasing demand for more energy coupled with the focus on environmental issues has encouraged intensive research into new sources of energy and clean fuel. Although inferior to other technologies in terms of installed capacity, photovoltaic (PV) is currently the most important Distributed Generation (DG) technology all over the world. The growth of the Italian solar market has been largely policy-driven and depended on financial support from the government since July 2005 FITs for photovoltaic energy systems were introduced. These tariffs have been revised until June 2013 when PV incentives were cut. To that date a total of 17.4GW of PV capacity from 549,877 PV systems were installed. Distributed grid-connected photovoltaic is playing an increasingly significant role in the Italian scenario as an electric supply resource and as an integral part of the electrical grid. As is well known, electricity systems can benefit from the integration of small-scale PV-DG. However PV poses notable challenges to grid engineers, planners and operators. An important challenge posed by grid-connected PV is the rapid output variations that occur when clouds cause shadows on panels. In this thesis the problem is addressed using neural network based techniques to forecast the output of PV plants and lithium batteries to smooth the power exported to the grid. Another problem faced is the efficiency loss due to hot temperatures. In this discussion a novel prototype of an active cooling system for PV module is presented. Another issue occurs when there is high penetration of PV in parts of the distribution system dominated by residential end-users and the amount of power generated by the PV exceeds the total demand. In this work energy management techniques are presented to shift household loads in the peak production hours and lithium batteries are used to store the excess of energy produced and reuse it during night time.

Keywords. Photovoltaic Systems, Artificial Intelligence, Italian Energy Market, Storage Systems.

1 Problem statement and objectives

Over the last decade renewable energy sources have had a great impact on European Union electricity production, following the approval of Directive 2001/77/EC, [1] which provided a framework for the development of renewable energy technologies in Europe. The European Commission continued supporting renewable sources with the directive, also known as the "20-20-20" targets [2], which sets as objective for EU in 2020 the achievement of a share of 20% from renewable sources in the consumed energy mix, the reduction of 20% of greenhouse gases emissions and the increase of energy efficiency to save 20% of EU energy consumption. Photovoltaic (PV) is currently the most important distributed generation (DG) technology in Europe. The European solar market growth has been largely policy-driven and depended on financial support from the government [3-4]. At the end of July 2005 the Italian Industry and Environment Ministers approved the introduction of FITs for photovoltaic energy systems. This long awaited law (called "First Conto Energia") has been introduced to grant 20-years incentives for systems between 1kWp and 1MWp. The Italian government defined the conditions and modalities for setting the special tariffs with a ministerial decree [5]. These tariffs have been revised until June 2013 when the Italian government took the decision to cut PV incentives to cope with soaring costs which reached to the financial cap of 6.7 billion euro. To 15th October 2013, a total of 17.4GW of PV capacity from 549,877 PV systems have been installed in Italy under the government's feed-in tariffs (FITs). As is well known, electricity systems can benefit from the integration of small-scale PV-DG. For instance, since distributed generation produces electricity where needed, it helps reducing the electric load on transmission lines and the need for costly new lines associated with new power plants far from towns and cities. However, PV poses notable challenges to grid engineers, planners and operators. An important challenge posed by grid-connected PV is the rapid output variations (ramping) that occur as clouds pass over panels. Sometimes and especially when having high penetration of PV in parts of the distribution system dominated by residential end-users, the amount of power generated by the PV may exceed the total demand being served by a given part of the distribution system. In those circumstances, "excess" power can have a dramatic effect on the electric service voltage. An important issue concerning PV technology is that the energy production efficiency of solar panels drops when the panel reaches hot temperatures. Another challenge of PV integration is that PV's maximum output tends to occur before the peak or maximum end-user demand. As a result of this mismatch, energy generated in the morning and early afternoon is less valuable than energy generated in the mid and late afternoons when, e.g., air conditioning use is the highest. In particular, all these problems concerning variability of PV output, efficiency losses and mismatch between power generation and peak demand make harder a complete integration into the electricity network and into the energy market. In this work a set of solutions to reduce the problems of the distributed generation are presented.

2 Research planning and activities

Both energy management of energy produced and storage addiction into PV systems need power production forecasts. The research of a valid and reliable forecasting scheme is thus a crucial task. This has been deeply investigated in the literature, in particular for the forecasting and power scheduling from wind plant [6]. However in recent years the prediction of solar irradiation has became more and more important especially in countries whose legislation encouraged the deployment of solar power plants [7]. Different approaches for modeling and forecasting solar irradiation may be appropriate depending on the application and the corresponding time scale. In particular two different approaches are proposed to obtain a valid and reliable prediction of the PV power output. The first approach consists of a two-staged method, where the solar radiation is firstly forecasted by using a Radial Basis Function Network (RBFN). In particular the considered input pattern for the network consists of: the hourly whether forecast, the number of day of the year, the hour of the day. The forecasted irradiation is then the input of a power output simulation model of the PV plants. For these PV systems with a unified configuration, a satisfying forecast accuracy of the power output can be obtained through this two-staged forecasting method [8-9].

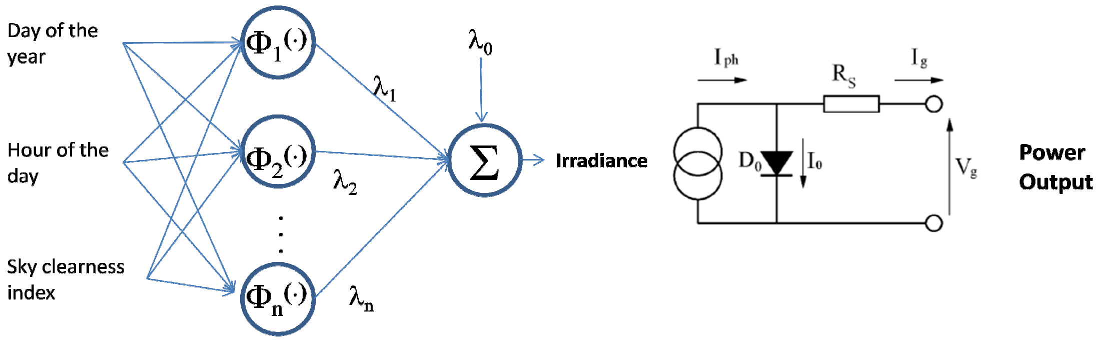


Figure 1. Scheme of the two stage PV output forecasting method.

The second approach aims to overcome the problem of different configurations in PV plants, using a one stage forecast technique of the output power reliable and easy-to-use [10]. The used algorithm is a RBF Neural Network with an on-line learning capability based on the Minimal Resource Allocating Network (MRAN) technique [11] and an Extended Kalman Filter. The main advantage of the proposed algorithm is that a large data set of irradiation measurements, weather forecast and temperature for a specific location are no longer required for the training of the NN; this drastically reduces the setup time. A further important advantage is that, due to the adaptive algorithm, some singular seasonal weather situation can be rapidly identified and corrected.

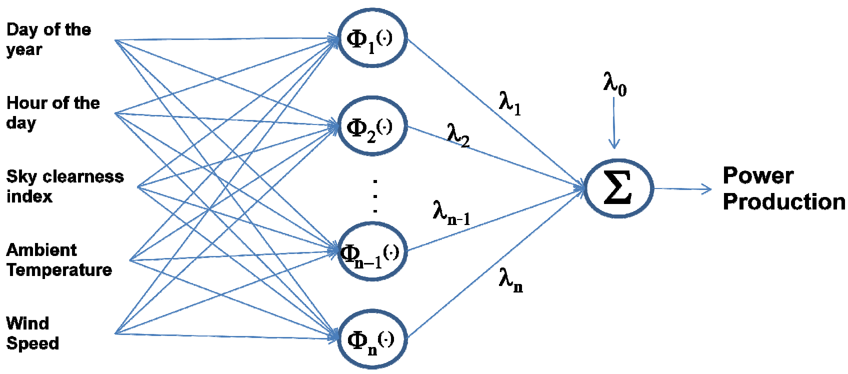


Figure 2. RBF network for the one stage MRANEKF forecasting method.

To minimize the problems due to the variable output of some distributed generation in this chapter it's analyzed the addition of energy storages into PV system architectures (in particular distributed energy storages [12-13]). In this chapter, divided into two main parts, the effects of a smart energy storage system are investigated. In the first part, the storage is used to to maximize self consumption [14]. In the second part, the storage is used as an energy buffer in order to feed the grid with a daily scheduled energy profile and "smooth out" variability that the grid must accommodate [15].

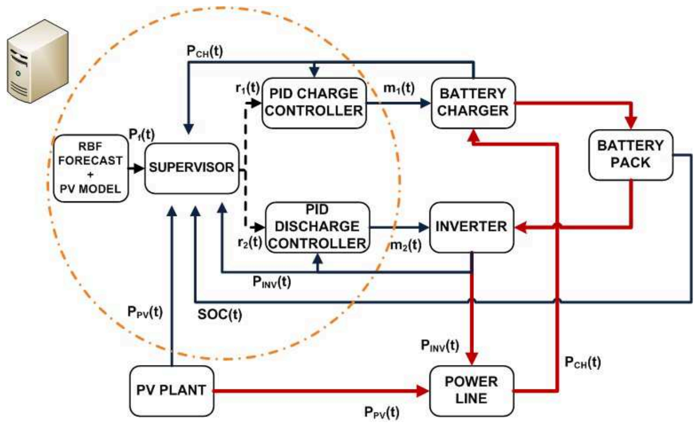


Figure 3. Storage system scheme.

The output of a solar cell, and therefore a solar panel, is affected by its temperature. As a result the power output reduces of between 0.25% (amorphous cells) and 0.5% (most crystalline cells) for each °C of temperature rise [16-17]. In warm climates panel temperatures can easily reach 50 °C in the summer, resulting in a 12% reduction in output compared to the rated output at 25 °C. This reduction in efficiency may be important if a high electricity demand in the summer is required. Hence, a new technology combining thermal and photovoltaic effects (Photovoltaic/Thermal PV/T) is developed [18-19]. A photovoltaic/thermal hybrid solar collector (or PV-T collector) is a combination of photovoltaic (PV) panels and solar thermal components. In fact, a PV-T component is defined as a device using a PV panel or PV cells as a thermal absorber. The aims of this technology are to cool the PV module and thus improve its electrical performance and to collect the thermal energy produced, which would have otherwise been lost as heat to the environment.

Figure 4. PVT module prototype.

The mismatch between peak power generation and peak power residential consumptions coupled with the incessant growth of domestic electricity tariffs made necessary an accurate management of home energy processes to obtain economic savings. However each household has a different pattern of energy consumption, and each energy generation system has its own advantages and disadvantages. It becomes necessary an accurate sizing of the PV systems to install [20] and the planning of energy management actions [21-22] for each specific dwelling. We developed a high-resolution "bottom-up" model of domestic electricity use, based upon a combination of patterns of active occupancy and daily household activities. The model, through a fuzzy logic inference system, gives as output the 1-minute resolution electricity usage pattern of each specific dwelling [23]. We used neural network based forecasts of consumption and PV production are used to develop energy management algorithms. Two different approaches are simulated and their effects evaluated through the household consumptions model [24-25]. The installation of all the devices needed to actuate proper EM policies can have a high cost compared to a residential PV system [26-27]. For this reason we present a case study on the proper sizing of a PV plant (in the central east region of Italy) and the evaluation of Energy Management potential benefits based on a costs benefits analysis (CBA) to set an upper limit for the equipment cost in order to obtain real savings for a specific household.

3 Analysis and discussion of main results

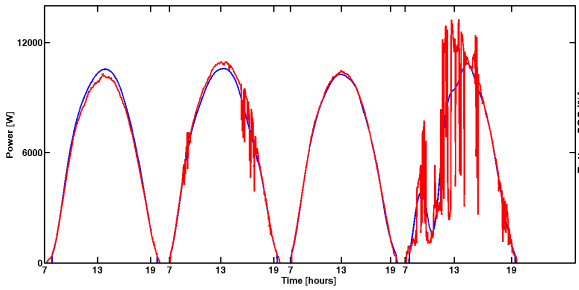
Concerning power production forecasts, results of both methods are compared. The training data set of the classical RBF Network (used for the two stages method) is composed by 5000 pairs of inputs-output and it is relative to the last 20 days of each month of 2010 as described in [9] while the MRANEKF Network is self learning [10]. Tests have been performed for different plants at different latitudes, in particular: Jesi (229 KWp, latitude 43,21N), Bussolengo (425 KWp, latitude 45,52N) and Galatina (212 KWp, latitude 40,12N). In all the considered tests results indicate that the proposed RBF MRAN algorithm realizes network with better prediction accuracy with respect to the two stage method RBF based. The normalized RMSE, SD and RMSE% have been used to summarize the experimental results (see Table 1).

Table 1. Comparison of the two production forecasting methods.

	MRANEKF (one stage method)			**RBF NN** (two stages method)		
DATA	**RMSE**	**SD**	**RMSE%**	**RMSE**	**SD**	**RMSE%**
Jesi	0,0671	0,0649	9,60%	0,0747	0,0701	13,80%
Bussolengo	0,0657	0,0632	9,10%	0,0732	0,0708	13,20%
Galatina	0,0663	0,0621	9,40%	0,0743	0,0712	13,30%

The storage experimental setup consists of 8 strings of Renergies 220P/220 polysilicon panels where each string is connected to a SMA Sunny Boy 1700IT solar inverter. A lithium battery pack consists of the series of two sub-module with 80 ThunderSky modules 40 Ah, a Battery Management System (BMS) and a battery charger for each module. A solar inverter (model SIAC soleil 10Kw) is connected to this pack. A power meter from Schneider Electric (model PM9P) is used to measure consumptions of the Energy Resources

R&D office considered for the tests. The software managing the setup is Labview based and contains the NN-based forecasting algorithm and the fuzzy logic supervisor. can provide the desired power to the line. In Fig. 5a and 5b are shown the predicted and provided power output of the PV plant and the corresponding trend of the battery state of charge (14-17 June 2012).



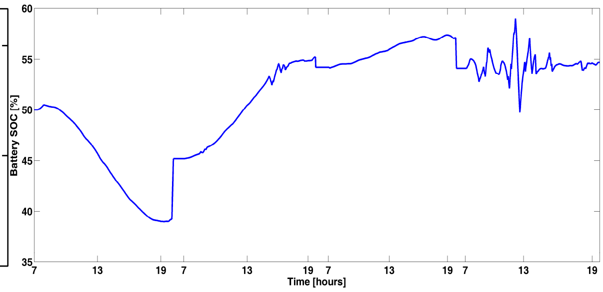
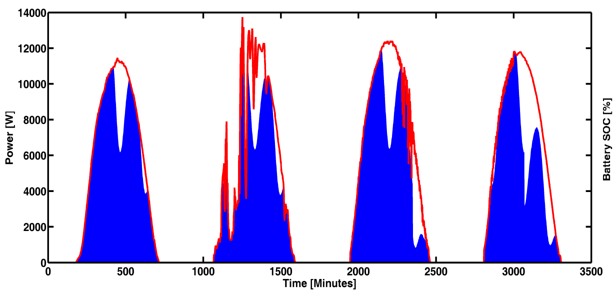


Figure 5a. Power produced and fed to the grid. Figure 5b. Battery SOC

The second application of the system concerns the maximization of the self consumption percentage of the whole produced energy. Tests show the ability to increase the selfconsumption rate by 18%, also protecting the battery without high rate of charge. In fig. 6a the red line is the power produced by the PV plant while the blue area is the energy consumed by the office and/or stored in the battery pack (12-15 July 2012). Fig. 6b shows the corresponding trend of the battery SOC.



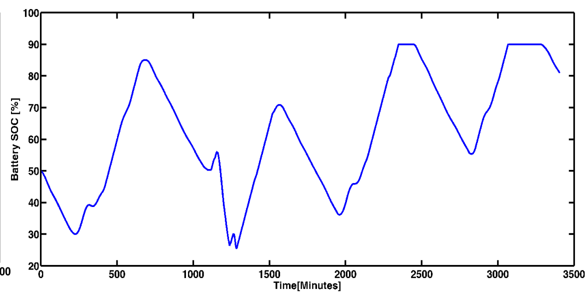


Figure 6a. Power produced and consumed. Figure 6b. Battery SOC

The novel prototype of the photovoltaic thermal collector has been tested during September 2012, in Jesi (AN), Italy. In particular both the traditional PV and the PV/T modules have been tested under the same environmental conditions (irradiation, air temperature, wind speed) and mounting (tilting and orientation). The experiments shown in Fig. 7 focuses on the comparison of the performances of the two modules under a water flow rate at 24 °C for the PV/T module: maximum cells temperature and AC power production. In particular the pumping circuit was activated according to a fuzzy logic control law, computing the water flow rate.

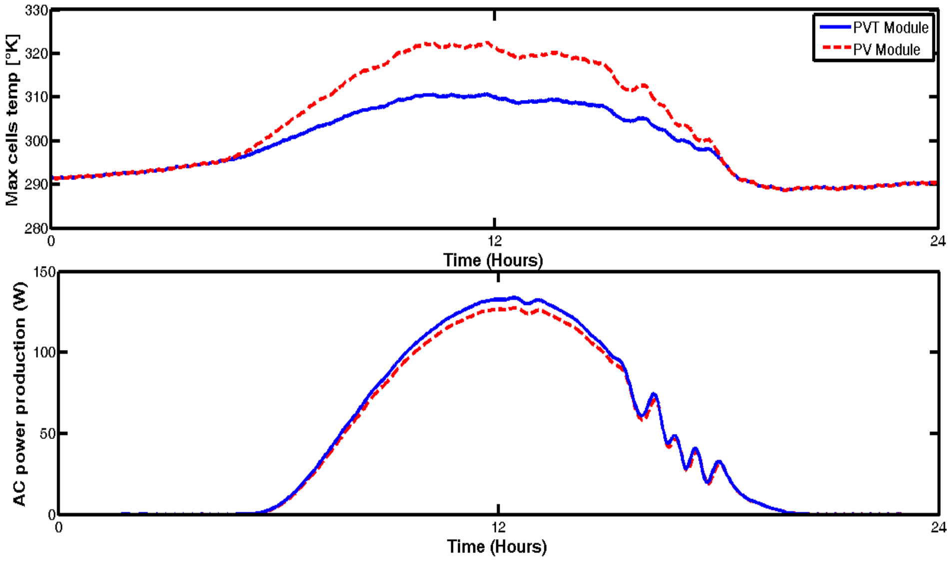


Figure 7. AC power production and cells temperature compared for the PV and PVT modules.

The tool has been used to correctly size a residential photovoltaic (PV) plant and simulate the effects of energy management techniques according to a cost benefits analysis (CBA). Net present value (NPV) and internal rate of return (IRR) have been computed for different sizes of PV plant in a case study. The obtained results, summarized in Table 2, show that in the new Italian scenario the NPV difference between the best and worst case can be 140% (which results in more than 1,200 €). Furthermore the economical benefits of energy management actions (shifting of the two main appliances) has been performed. The CBA analysis shows that revenues can further increase from 250 to 600 € (depending on the plant size) thus imposing cost limitation for the EM equipment.

Table 2. Unitary costs, self consumption percentages (SC) and CBA results (NPV and IRR) for the considered case study with and without energy management actions.

		No EM actions			**EM actions**		
Size (KWp)	**Cost (€/KWp)**	**SC (%)**	**NPV (e)**	**IRR (%)**	**SC (%)**	**NPV (e)**	**IRR (%)**
1.00	3850	41.1	787	7.91	53.4	1005	8.64
1.25	3750	35.3	937	7.85	47.3	1208	8.60
1.50	3500	31.3	1251	8.35	42.9	1566	9.11
1.75	3150	27.4	1711	9.28	38.5	2067	10.07
2.00	2950	24.2	2048	9.71	35.2	2443	10.51
2.25	2750	22.5	2069	9.47	32.9	2501	10.30
2.50	2700	20.6	1730	8.51	30.6	2198	9.36
2.75	2500	19.4	1716	8.42	29.4	2215	9.32
3.00	2450	17.5	1363	7.60	26.9	1888	8.51
3.25	2320	16.2	1310	7.46	25.8	1879	8.44
3.50	2260	15.7	1047	6.89	24.7	1624	7.85

4 Conclusions

The variability of PV output, efficiency losses and mismatch between power generation and peak demand make harder the complete integration of PV systems into the electricity network and into the energy market. In this work a set of innovative solutions to overcome these problems have been provided. Two different methods to compute hourly site-specific PV production forecast have been proposed and their performances compared. A smart storage system with a fuzzy logic based supervisory control system has been proposed. On-line tuned neural network have been considered to forecast the PV production and power mismatch between PV production and consumption. These forecasts are used by the supervisor to manage the power flows, feeding the line with a scheduled power profile, increasing the self consumption and preventing damages to the battery. We presented also the prototype of a novel photovoltaic and water heating system (PVT). We showed the performance improvements with respect a traditional PV module and tested a fuzzy controller that can improve the electrical performances of 6% with respect a traditional PV module and save 9% more water with respect a traditional PI-based controller. In the end we presented a novel Fuzzy approach to model household electrical consumption and the design of home energy management algorithms based on neural network forecasts of production and consumptions. The model has been used to correctly size a residential photovoltaic (PV) plant and evaluate the effects of energy management techniques according to a cost benefits analysis (CBA).

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