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Controlled power distributed photovoltaic system using solar energy forecast

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Abstract. The use of renewable energy sources to supply electricity in customer grids is a current practise in developed countries and, particularly, in the case of distributed solar energy generation grids. Even though, the environmental benefits of the practise drive to economic incentives to increase the renewable energies. However, because of the unsteady behaviour of the renewable electric energy sources [1], as wind energy and solar photovoltaic production, the increment in the use of these sources produces severe fluctuations in the electric grids. Then, their electric supply to the electric grid is limited and at the same time, an accurate renewable energy production forecast is required.

In this work, the feasibility of a new approach to reduce this problem is tested by the application (on a yearly basis) of a simulator of a production-storage controlled system, namely FOTOV, to be applied in the design of a photovoltaic (PV) installation.

Key words

PV system with storage, predictive control, solar radiation forecast, FOTOV simulator.

1. Introduction

Currently countries generate most of their electricity in large centralized facilities, which have excellent economies of scale, but there is an amount of energy lost in transmitting electricity, and the size and number of power lines starts to be an important problem. An alternative to this scheme is to include the distributed generation resource systems, which are small-scale power decentralized generation technologies used to provide an alternative to central electric power system. The injection of electric power from unsteady renewable energies, as wind and photovoltaic systems, in the customer networks is growing in the developed countries, mainly because they are qualified as clean energies. However, the intermittent nature of these energy sources produces a risk of power unavailability that the electric networks not always can manage. In several countries the electric network managers include specific conditions to allow the injection of unsteady energy production from renewable sources. Particularly, both for wind and PV systems an hourly production forecast is required, as these systems are requested to report the future production (6 to 30 hours in advance) and, after that, to guarantee this production. As wind and PV production depend on the weather (wind and solar radiation), the reliability of these systems depend on the accuracy of the weather forecast applied.

However, during some periods the energy production can be higher than expected; in this case, storage devices can be applied to store this temporal excess of energy to be injected in periods with deficit, improving the reliability of the production system. As a consequence, this system can guarantee a more stable production, close to the production forecast.

The use of this kind of production-storage (PS) system requires a control algorithm based in the production forecast as setpoint, following a feedforward approach. Adjust of the control parameters depends on the fluctuations of both actual and forecast energy productions; therefore, the use of a software simulator is highly recommended.

In addition, previous experiences in the use of batteries as storage systems [2] shock with the problem of their durability. Other studies [3] show the use of capacitors, which provide a daily modulation of the power output; although its application is limited by the price of these storage systems, capacitors demonstrated their reliability in PV applications.

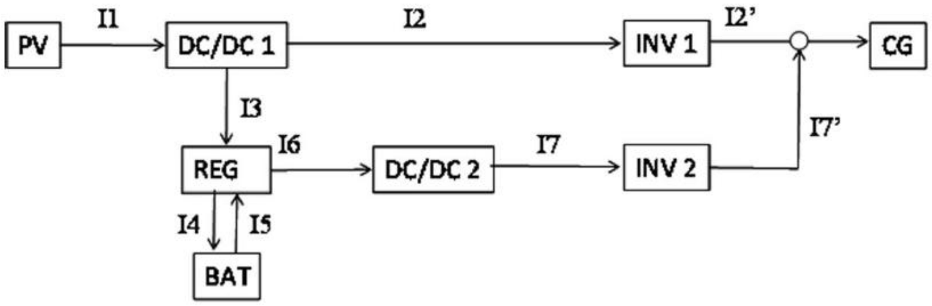

Fig. 1. Scheme of the PS controlled system adapted to a PV installation. The following acronyms are in use: PV - Photovoltaic panel, DC/DC - Controllers, REG - Charge regulator, BAT - Batteries, INV - Inverter and CG - Customer grid.

The optimum storage size (OSS) is a key parameter in the design of any production-storage system for unsteady renewable energies exploitation. The use of a simulator of this production-storage system will allow the estimation of the OSS, considering the hourly variability of the energy production. This OSS can be adapted to any storage device depending on their technical specifications.

In this work, a simulator of the PS controlled system was developed and tested along one year. This simulator has been applied to a PV grid connected PS system (Fig. 1), using WRF [4] numerical weather forecast model to provide solar radiation forecast data for the production forecast. Control parameters have been adjusted to assure a stable output, and OSS was calculated at different locations.

2. Simulator and control algorithm

A predictive control system was designed in order to reduce the fluctuations of electric supply from the photovoltaic installation.

In order to test the control system, a numerical model (namely, FOTOV) a PV grid connected system with control and energy storage, as shown on Fig. 1. The photovoltaic intensity (I1) is divided by the DC/DC1 distributor depending on the production forecast (PRED); that is, if I1 is higher than PRED (production excess), part of I1 is derived to I3 to be stored in the batteries. On the other hand, if I1 is less than PRED (low production), DC/DC2 converter is adjusted to demand from the batteries an intensity I7 = (PRED - I1).

Considering the response time of the system (due to the solar radiation fluctuations), a predictive proportional approach to adjust both DC/DC converters were proposed for testing. Following the scheme on fig. 1, the distributor DC/DC1 produces the intensity I2 as follows,

$$I2 = k11 \cdot I1 \qquad (1)$$

with k11 as the first control parameter for DC/DC1, with a value depending on the control algorithm.

Intensity I2 reaches the INV1 inverter that convert DC to AC for injection to the electric grid. If I1 is higher that the production forecast, PRED, intensity I3 is derived by the DC/DC1 distributor, as follows,

$$I3 = k12 \cdot I1 \qquad (2)$$

with k12 as the second control parameter of DC/DC1. Of course, the relationship between k11 and k12 is,

$$k11 + k12 = 1 \qquad (3)$$

Although this can reduce the DC/DC1 control parameters to only one (typically, k11), both parameters were kept in order to add flexibility to the control module.

Intensity I3 is the input of the batteries (BAT) regulator (REG); its charge/discharge process is represented by I4/I5 intensities, which are managed automatically by the regulator depending on I3, the batteries load (BAT) and the energy demand to the batteries, I6. This demand can be computed depending on the production deficit, I7 and the inverter INV2 efficiency. However, in an actual installation a DC/DC2 distributor is required in order to limit the energy demand I7, because the commercial regulators (REG) usually supply all the intensity required (when available). Therefore, the DC/DC2 controlled includes a control parameter k21 defined as,

$$I7 = k21 \cdot I6 \qquad (4)$$

Depending on the value of I7 required to achieve the forecast production (PRED) added to I2, the algorithm computes the appropriate value for k21. As for the I2 intensity, I7 reach to the INV2 inverter, reducing its value due to the inverter efficiency. Then, the actual production of the FOTOV controlled system will be,

$$PROD = I2 + I7 \qquad (5)$$

Ideally, this value has to achieve the forecast production (PRED) to guarantee the stability of the system.

The functionality of this controlled system can be summarized in four different cases included in table 1. Cases 1A and 1B correspond to an excess of PV production respect to PRED (I1 > PRED), so depending the charge level of the batteries the extra energy will be either stored (1A) or dissipated (lost) (1B); this latter case is not desirable, so the capacity of the batteries should be enough to minimize this lost energy.

Cases 2A and 2B correspond to a deficit in PV production, so an extra energy supply from the batteries is necessary (case 2A), in order to achieve PRED in the system output. However, if the batteries level is too low (namely, empty batteries) no extra energy can be provided, so the system production will not achieve PRED (case 2B); again, this latter case is not desirable, so the capacity of the batteries should be enough to avoid this.

Table 1. Different functional modes of control and parameters associated to every DC/DC distributor. Case 1 (I1 > IPRED) indicates an excess of PV production respect to forecast power and case 2 (I1 < IPRED) corresponds to a deficit in PV production.

Case	Battery state of charge	Parameters			
		k11	***k12***	***k21***	***k22***
I1>IPRED (1)	No fully charged battery (1A)	k1C	1-k1C	0	0
	Fully charged battery (1B)	k1C	1-k1C	0	1
I1<IPRED (2)	No empty battery (2A)	1	0	k2C	0
	Empty battery (2B)	1	0	0	0

From the analysis of the system and the control paradigm proposed, values for the parameters k1C and k2C can be derived, as follows,

$$k1C = \frac{E}{I1} \tag{6}$$

$$k2C = \frac{E - I1}{IBAT} \tag{7}$$

where E is the control error, that depends on the production forecast. Several functions can be defined for this error; the most simple is,

$$E = PRED \tag{8}$$

However, the validity of this error function depends on the stability of the system. FOTOV model allows the estimation of the values of the control parameters during the system design.

About the selected setpoint, in classical control systems of processes ([5], [6]) one or several setpoint values are usually adopted from the design values. However, when the process output depend on either external variables or complex relationships, a predictive control is more feasible. In this second case, the setpoint is obtained from the forecast process variables, applying a system model.

In our case, the system output depends on the global solar radiation, which is an external non-controlled variable; then, the PV production can be estimated either from a linear function provided by the manufacturer or, even better, from a linear regression of PV production vs. solar radiation measurements at every location. Anyway, for a predictive control a PV production forecast is required. Typically, global solar radiation can be estimated in advance by a numerical weather forecast model; the use of this approach has been extensively tested [7]-[9].

In this work a high resolution implementation of WRF model ([4]) for the testing region was done, in order to improve the spatial accuracy of the solar radiation forecast. However, during cloudy days some discrepancies between model results and measurements were expected, mainly because of the difficulty to forecast the clouds development and transport over a single location.

3. Results

Three different locations at the NW of Galicia were selected for the forecasts testing: one in the Atlantic coast (CIS-Ferrol), 34 meters above sea level (asl-m), and the others placed inland, around 32 km (Santiago-EOAS, 255 asl-m) and 30 km (D1-A Mourela, 450 asl-m) far from the sea, respectively. CIS-Ferrol and Santiago-EOAS are weather stations classified as suburban and urban stations, respectively; whereas D1-A Mourela is a rural site.

The sunshine hours are even lower than the regional average (less than 2000 sunshine hours per year) in some of these stations, with values between 1600 and 1800 hours per year at the northern locations (CIS-Ferrol and D1-A Mourela) and around 2000 hours at EOAS-Santiago station [10].

Measurements of global solar radiation were obtained from Class A pyranometers installed at every location. The manufacturer linear function for a PV-type panel to be installed was applied in order to estimate the energy production from global solar radiation measurements. Yearly optimal azimuth and slope for the panels at every location were considered.

The simulator FOTOV was applied to study the theoretical behavior of the proposed system, in order to evaluate the maximum profit and to estimate the optimum storage size (OSS). WRF meteorological model forecasts and historical irradiance data used to evaluate the control system are explained as follows.

An original synthetic ensemble of WRF results [11] is considered to estimate the hourly photovoltaic production forecast (24 hours in advance), as control setpoint. Irradiance measurements from July 2010 to June 2011 were applied to estimate the actual photovoltaic production.

Numerical simulations of this PV controlled system were performed at three different sites (rural, suburban and urban) using hourly (D1-A Mourela) and 10-minutes (Santiago-EOAS and CIS-Ferrol) average solar radiation data, in order to estimate the reduction in energy supply fluctuations obtained with this control system, and the energy savings.

For the evaluation of the control system performance, different parameters were computed at the end of the simulation period: ESD, as the deviation of energy supply (%), respect to the predicted; and, WEN, as the wasted energy (%), respect to the supplied by the photovoltaic system. These two first parameters are related to the efficiency of the FOTOV control to reduce the fluctuations of electric supply from the photovoltaic installation due to the inaccuracy of the irradiance forecasting.

In a first stage, an ideal operation of the system (including the batteries charge/discharge cycle) was considered. That is, the batteries can be discharged to 0%, so the storage system size obtained corresponds to the minimum size. With this approach, simulations were performed in the range from 0 (no storage system) to 400 Ah. In addition, at the beginning of the year simulation the batteries could be partially charged (due to previous photovoltaic production), affecting to the final result; therefore, different initial charge levels were considered: empty, 30%, 50% and full (100%).

Figure 2 shows these parameters at CIS Ferrol station starting with empty batteries, for the range of storage sizes tested, and considering an ideal 0-100% batteries charge/discharge regime: that is, batteries can be discharged until they are empty, and can be charged with any load until 100%. Results show that both ESD and WEN keep constant above a 80 Ah of batteries capacity, with less than 1% and 6%, respectively.

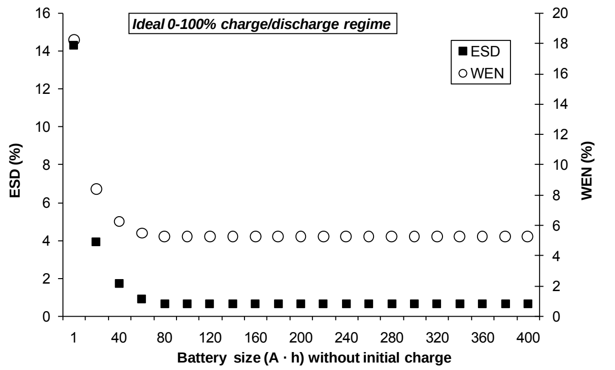

Fig. 2. Influence of battery size on FOTOV performance in the CIS-Ferrol weather station. Evaluation benchmarks applied were ESD and WEN. This simulation considers empty batteries and a 0-100% charge/discharge battery regime.

Therefore, it is clear that the use of an optimum storage size reduces the energy waste and, increases the energy supply; although an initial battery charge can be required to drop ESD to 0.

Considering that a more realistic charge/discharge battery cycle can affect the system performance, a more restrictive hysteretic charge/discharge regime was set up: maximum battery discharge is limited to 30% of the full charge of the battery and, if this limit is reached, the battery can only supply energy when the 50% of the total charge is reached.

Figure 3 shows the results of the evaluation parameters for different batteries capacities at CIS Ferrol station with this restrictive regime. It is observed that an increase in the capacity above the optimum size (120 Ah) increases ESD. This behaviour is due to the larger batteries, as if they are discharged below 30%, more charge is necessary (at least, 50%) to supply energy to the circuit again; therefore, during this charging period batteries are not available to supply energy and more failures in the supply to the electric grid can be achieved.

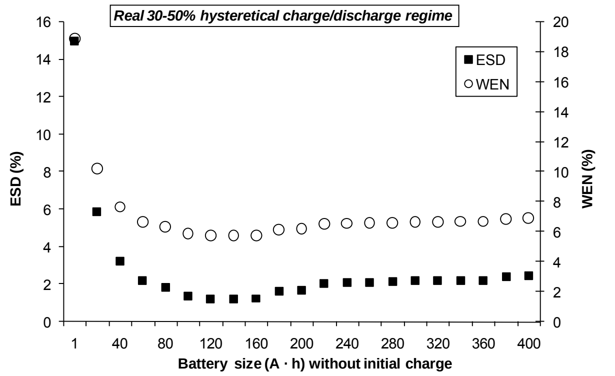

Fig. 3. Influence of battery size on FOTOV performance in the CIS-Ferrol weather station. Evaluation benchmarks applied were ESD and WEN. This simulation considers empty batteries and a 30-50% hysteretic charge/discharge battery regime.

Table 2 shows the performance of the PV system with and without batteries in three stations. There is dependence of the OSS from the charge/discharge battery cycle. Batteries with 30-50% hysteretic charge/discharge battery regime should have greater capacity than 0-100% charge/discharge battery regime. This result shows that the battery size is dependent on the location of the installation, as it is expected. However, the system control can achieve a good performance in any of these locations with the appropriate battery size.

Table 2. Comparison of the performance of the PV system with and without batteries, considering both ideal and hysteretic charge/discharge regimes (with OSS). Results for CIS Ferrol, Santiago EOAS and D1-A Mourela stations.

Charge/Discharge regime	Storage system	CIS Ferrol			Santiago EOAS			D1-A Mourela		
		OSS (Ah)	ESD (%)	WEN (%)	OSS (Ah)	ESD (%)	WEN (%)	OSS (Ah)	ESD (%)	WEN (%)
	None	-	15.0	18.9	-	13.1	17.2	-	14.1	17.4
Ideal 0-100%	Empty battery	80	0.6	5.2	140	0.4	5.1	160	0.4	4.3
Hysteretical 30-50%	Empty battery	120	1.2	5.8	200	1.1	5.7	200	1.8	5.6

4. Conclusions

Simulator of the PV controlled system with electric energy storage has proved its reliability to improve the energy supply to a customer grid, considering both the fluctuations of the solar radiation forecast against measurements and the appropriate size of the electric storage system.

Results for one year simulation show a reduction in the PV production not supplied to the customer grid from 15% (no batteries) to 1-2% (with the optimum batteries size), depending on the accuracy of the solar radiation forecast at different locations. In addition, the simulator shows to be useful to estimate the optimum batteries size for every location, especially for batteries with hysteresis in the charge regime. For example, in the two of the locations tested, the optimum sizes were 200 Ah (inland urban and rural stations) and 120 Ah (coastal suburban station).

Therefore, this simulator can be coupled to typical PV systems design software in order to estimate not only the PV panels required, but also the optimum storage size to be applied in a PV controlled system.

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