PREDICTIVE CONTROL SYSTEM FOR MODULATED SUPPLY OF PV ENERGY

J.A. Souto, A. Rodríguez
S. Saavedra, J.J. Casares
Department of Chemical Engineering
University of Santiago de Compostela
15782 Santiago de Compostela, Spain
+34 881 816 757 (ja.souto@usc.es)

A. Garcia-Loureiro
Department of Electronics and Computer Science
University of Santiago de Compostela
15782 Santiago de Compostela, Spain

R. Varela, M.J. Legarreta
J. Rodríguez-Aneiros
CIS-Galicia
A Cabana, s/n, 15590 Ferrol
Spain

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. However, because of the unsteady behavior of the renewable electric energy sources, as solar photovoltaic production, it produces fluctuations in the electric grids; then, an accurate renewable energy production forecast is currently required. In addition, errors in the production forecast can be solved by using a production-storage controlled system.

In this work, a predictive control system was designed in order to reduce the fluctuations of electric supply from the photovoltaic installation, taking into account a solar radiation forecast provided by WRF (Skamarock and Klemp, 2008) numerical weather forecast model. Numerical simulations of this PV controlled system were performed at two different sites (coastal suburban and inland urban) using hourly and 10-minutes average solar radiation data, in order to estimate the reduction in energy supply fluctuations obtained with this control system.

The results show that the energy supplied is increased by 12% using this control system, respect to the use of the solar radiation forecast without energy storage. In addition, an optimum storage size for every site can be estimated from the simulations results, taking into account both the energy production and the minimum storage size required.

Key words

Solar Radiation

1 Introduction

The injection of electric power from unsteady renewable energies, as photovoltaic (PV) systems, in the customer grids is increasing 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 grids not always can manage. Therefore, for PV systems a solar radiation forecast is highly recommended. As PV production depends on the weather conditions, the reliability of these systems depend on the accuracy of the solar radiation forecast applied.

However, during some periods the PV 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 modulate the energy injection, close to the production derived from the solar radiation forecast.

Introducing an electric energy storage system should consider both durability and price of the hardware (Garche et al, 1997; Rahman and Yamashiro, 2007). However, previously to these factors, the optimum storage size must be defined. In this case, the optimum storage size (OSS) is a key parameter in designing any production-storage system. This parameter can be obtained from a model of the PV system with control, considering the variability of the solar radiation and its influence in the energy production.

In this work, a grid connected PV system with energy storage is modeled and tested at different locations. WRF numerical weather forecast model provides the solar radiation forecast to estimate the PV production, as control setpoint. Control parameters have been adjusted to assure a stable output, and OSS was calculated as a function of the bias production.

2 The FOTOV simulator

FOTOV is a model of a PV grid connected system with control and energy storage, as shown on figure 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

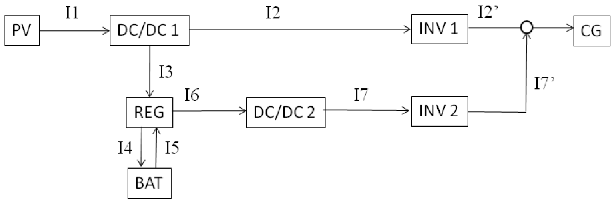

Figure 1. Scheme of the PS controlled system adapted to a PV installation. The following acronyms are in use: PV - Photovoltaic panel, DC/DC - Controllers, REG - Charge regulator, BAT - Batteries, INV - Inverter and CG - Customer grid.

PRED (low production), DC/DC2 converter is adjusted to demand from the batteries an intensity I7 = (PRED - I1). Other cases were described jointly to the control algorithm in Section 3.

Because of the natural variability of the solar radiation and, as a consequence, of the photovoltaic production, adjusting of the DC/DC distributors can fail due to either too slow or fast changes in the output intensities I2 and I7. In addition, the capacity of the batteries could be not enough to achieve the production forecast at any time. In this case, the FOTOV model can be applied to estimate the required capacity to assure the production in a specific location, depending on the solar radiation received.

3 The control algorithm

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,

$$I2 = k11 \times I1 \tag{1}$$

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 network, considering the inverter efficiency.

If I1 is higher that the production forecast, PRED, intensity I3 is derived by the DC/DC1 distributor, as follows,

$$I3 = k12 \times I1 \tag{2}$$

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

$$k11 + k12 = 1 \tag{3}$$

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

Intensity I3 is the input of the batteries (BAT) regulator (REG); typically, a commercial regulator is used in the photovoltaic installations with the ability of protecting the batteries against either too high or too low loads. This load/unload 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.

The energy demand I6 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,

$$I7 = K21 \times I6 \tag{4}$$

Depending on the value of I7 required to achieve the forecast production (PRED) added to I2, this 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,

$$PROD = I1 + I7 \tag{5}$$

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

The functionality of PS 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.

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

$$k1C = \frac{E}{I1} \quad (6)$$

$$K2C = \frac{E - I1}{IBAT} \quad (7)$$

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

$$E = PRED \quad (8)$$

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

About the selected setpoint, in classical control systems of processes (Marlin, 2000; Svrcek et al, 2000) 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 (Zamora et al., 2005; Lorentz et al, 2009; Prabha and Hoogenboom, 2010).

In this work a high resolution implementation of WRF model (Skamarock and Klemp, 2008) 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.

4 Results

For a realistic testing of FOTOV model, different locations with continuous solar radiation measurements at Galicia were considered. This region is located in the NW of the Iberian Peninsula and its weather is characterized in terms of solar radiation by one of the lowest number of sunshine hours in the Iberian Peninsula ($<$ 2000 sunshine hours per year). In addition, sunshine distribution is variable along the year and between different locations, depending on their specific local conditions.

Therefore, two different locations at the NW of Galicia were selected for testing: one in the Atlantic coast (CIS-Ferrol), 34 meters above sea level (asl), and the other placed inland, around 32 km (Santiago-EOAS, 255 m asl) from the coast. CIS-Ferrol is classified as suburban site and Santiago-EOAS as urban station. Sunshine hours are even lower than the regional average, with values between 1600 hours per year at the northern locations (CIS-Ferrol) and around 2000 hours at Santiago-EOAS station (Precedo-Ledo et al, 2001).

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.

FOTOV model was applied to study the theoretical behavior of the proposed system, in order to evaluate its 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 (Saavedra et al., 2011) is considered to estimate the hourly photovoltaic production forecast (24 hours in advance), as control setpoint. Irradiance measurements from May to October 2010 were applied to estimate the actual photovoltaic production. Simulations were done considering 10-min average data measurements, in order to take into account possible fluctuations of the solar irradiance along every hour.

For the evaluation of the control system performance, different parameters were computed at the end of the simulation period:

ESD: Deviation of energy supply (%), respect to the predicted.
WEN: Wasted energy (%), respect to the supplied by the photovoltaic system.

This 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 6-months 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%).

Table 1. Different functional modes of FOTOV system and control 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	k11	k12	k21	K22
I1 $>$ IPRED(1)	Non fully - charged battery (1A)	k1C	1-K1C	0	0
I1 $>$ IPRED(1)	Fully charged battery (1B)	k1C	1-K1C	0	1
I1 $<$ IPRED(2)	Non empty battery (2A)	1	1-K1C	k2C	0
I1 $<$ IPRED(2)	Empty battery (2B)	1	1-K1C	0	0

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 and Santiago EOAS stations.

Charge/Discharge regime	Storage system	CIS Ferrol			Santiago EOAS		
		ASS (Ah)	ESD (%)	WEN (%)	ASS (Ah)	ESD (%)	WEN (%)
Ideal 0-100%	None	-	12.2	14.2	-	10.9	13.6
	Full battery	60	3.1	6.3	60	1.4	5.3
Hysteretical 30-50%	None	-	12.8	14.7	-	11.4	14.0
	Full battery	60	3.6	6.8	80	1.5	5.8

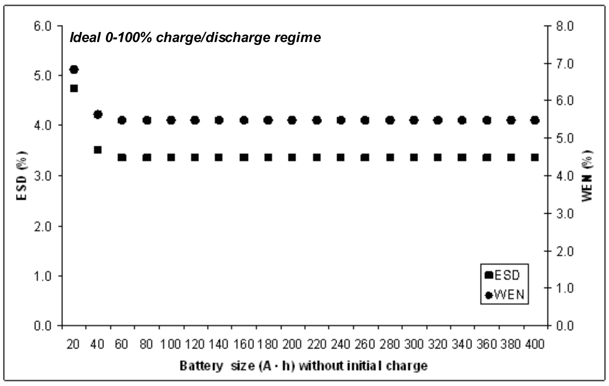

Figure 2. Influence of battery size on FOTOV performance in the CIS-Ferrol weather station. Evaluation benchmarks applied were ESD and WEN. This simulation considers empty batteries and a 0-100% charge/discharge battery regime.

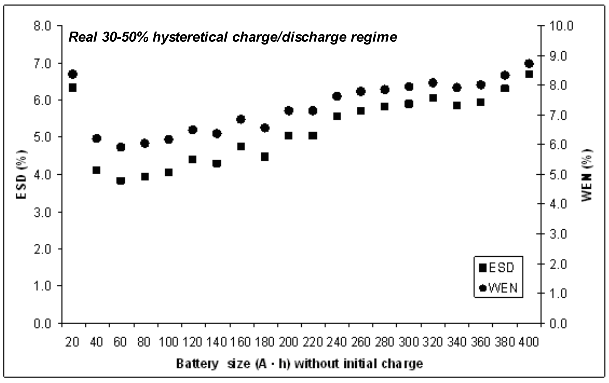

Figure 3. FIG 3Influence of battery size on FOTOV performance in the CIS-Ferrol weather station. Evaluation benchmarks applied were (a) ESD and WEN and (b) BAC, BLU, UES and NFB. This simulation considers empty batteries and a 0-100% charge/discharge battery regime.

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 60 Ah of batteries capacity, with less than 4% and 6%, respectively.

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.

At EOAS station (tabla 1), OSS is slightly higher (80 Ah) and different than the chosen battery size with an ideal cycle (60 Ah), but the values of ESD and WEN are lower. There is no dependence of the OSS from the charge/discharge battery cycle. 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.

5 Conclusions

Modeling of the PV controlled system with energy storage, using FOTOV model, has proved its reliability to improve the energy supply to a customer grid, considering both the fluctuations of the solar radiation forecast from measurements and the appropriate size of the storage system.

The simulation of the PV controlled system was run along the same 6-months period, considering a solar radiation synthetic forecast obtained from WRF ensemble forecast, but artificially corrected to get a zero mean bias along the period. Of course, hourly fluctuations in the forecast errors remain, so they should be modulated by the control system.

Results for this 6-months simulation show a reduction in the PV production not supplied to the customer grid from 15% (no storage system) to 2-4% (with OSS), depending on the accuracy of the solar radiation forecast at different locations. In addition, simulations show to be useful to estimate the OSS for every location, especially for storage systems with hysteresis in the charge regime. For example, in the two locations tested, OSS values were 60 Ah (coastal suburban station) and 80 Ah (inland urban station). Therefore, FOTOV model 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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