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SYSTEM MODELLING AND ENERGY MANAGEMENT FOR GRID CONNECTED PV SYSTEMS WITH STORAGE

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ABSTRACT: This paper presents the modelling and energy management of a grid connected PV system associated with storage. Within the economic, energetic and environmental context, objective of the system is to ensure loads supply at the least cost by optimising the use of solar power. Therefore, due to the complicated operating patterns, an energy management system which decides on energy flow for any moment is necessary. First, we present the system studied. Based on an AC bus typology, we consider all the energy flow possibilities. A model of the system is presented with an innovate algorithm for the estimation of batteries state of charge (SOC). Energy management has been done with a deterministic algorithm. At each step size, the algorithm finds the energy flow pattern which ensures loads supply at the least cost, taking into account availability of PV power, batteries SOC, loads demand and instantaneous electricity grid prices.

1. Introduction

Face up to the environmental, economical and political context, integration of renewable energy in electricity production is essential. Due to its many assets, photovoltaic solar power is one of the most promising solutions. However, over voltage in distribution lines network during important feeding time and the mismatch between the PV production and the loads consumption times impose the limits of integration of grid connected PV systems [1]. Adding a storage element to these systems would enable to solve these problems. In such a case, many applications are conceivable, depending of size and technology of the storage element. The high number of power flow direction has to be considering in function of the architecture of the system. To satisfy the objective function of the system, a power flow management algorithm has to be developed. Forecasting of variables in the system such as grid electricity price and solar source availability are necessary to ensure optimization along the period studying. This paper presents the hybrid system and its corresponding power flow possibilities. Modelling of the PV source and storage are displayed. Determinist algorithm has been used to develop the power flow management algorithm. This algorithm and its corresponding objective function are described for an individual economic environment. Simulations have been realized in a perfect prediction context. Results are analysed and discussed.

2. System description

In this paper, we propose to integrate a storage element in a grid connected photovoltaic system. The storage technology used in this study is lead acid secondary batteries. Because the storage is associated with a commercial grid connected PV system, topology of the global system is composed of an AC bus. Figure 1 shows the scheme of the system with the possible power flow directions and their corresponding signs convention. Photovoltaic modules are considered as a power source, loads as a power sink, batteries and grid are considered as power sources or sinks depending of the power direction.

![Figure 1: Scheme of the system studied](image-url)

### Table 1: System specifications

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{loads\ max}$</td>
<td>2.8 kW</td>
</tr>
<tr>
<td>$P_{ppv}$</td>
<td>3.5 kW</td>
</tr>
<tr>
<td>$P_{bat\ max}$</td>
<td>2 kW</td>
</tr>
<tr>
<td>$C_{bat}$</td>
<td>200 Ah</td>
</tr>
<tr>
<td>$V_{bat}$</td>
<td>120 V</td>
</tr>
</tbody>
</table>

The reference loads consumption profile and grid electricity prices are presented Figure 2. The PV purchase price is a constant equal to 0.3 €/kWh. The on peak and off peak periods are based on the actual end user electricity contract, from the grid operator GEG in Grenoble, France [2]. Prices values have been evaluated considering to be expected in a future liberalised electricity market. The loads power demand profile has been created with information about french electric consumption from [3]. City of simulation is Chambéry, in France. Hourly irradiation and temperature values for the year 2007 are collected from experimental measure at INES institute, Chambéry.
3. System modelling

3.1. Photovoltaic generator

The PV module current/voltage behaviour at the maximum power point (MPP) is described through linear equations (1), (2) and (3) [4]. The module temperature \( T_{mod} \) (°C) is obtained from the nominal operating cell temperature \( NOCT \) (°C), the ambient temperature \( T_{amb} \) (°C), and the irradiance \( E \) (W/m²). Taking into account the temperature effect, output current and voltage are obtained from the standard test conditions (STC). By this way, the only parameters needed are temperature coefficients \( C_{I_{mpp}} \) (A/°C) and \( C_{V_{mpp}} \) (V/°C), the \( NOCT \), STC irradiance \( E_0 \) equal to 1000 W/m², STC current \( I_{stc} \) (A) and voltage \( V_{stc} \) (V), and cell temperature \( T_{stc} \) (°C). These data are always given by the constructor.

\[
T_{mod} = T_{amb} + E/800 \times (NOCT - 20) \tag{1}
\]

\[
I_{mpp} = [I_{stc} + C_{I_{mpp}} \times (T_{mod} - T_{stc})] \times E/E_0 \times Np \tag{2}
\]

\[
V_{mpp} = [V_{stc} + C_{V_{mpp}} \times (T_{mod} - T_{stc}) + 0.026 \times \log (E/1000)] \times E/E_0 \times Ns \tag{3}
\]

Total current and voltage of the PV generator are obtained by multiplying module current and voltage respectively by the number of modules in parallel \( Np \) and in series \( Ns \). As the equations shows, we consider the PV generator working at its MPP. Behaviours of the MPPT and inverters are not modelled here. The mean efficiency of power electronic is taking into account with a ratio of 92% applied to the output power of the PV generator.

3.2. Lead acid battery

This section presents only the state of charge. We do not model the voltage characteristic because it is not needed for energy management.

We propose here an innovating estimation of SOC from [5] describes by equations (4) (5) (6) (7). It takes into account the variation of the quantity of charge in the process as a function of the current rates and temperature. Values needed to SOC estimation are the reference capacity and its corresponding current. \( Cn_0 \) (Ah) is the new nominal capacity after the discharge number “n”. This nominal capacity tapers off with ageing process after each discharge. Evolution of this quantity is described in the subsection about state of health (SOH); \( C(t) \) (Ah) is the available quantity of charge in the battery at time “t”; \( Q(t) \) (Ah) is the initial quantity of charge in the battery at time \( t_0 \); \( Qd(t) \) (Ah) is the quantity of charge which take part in the discharge process; \( Qc(t) \) (Ah) is the quantity of charge which take part in the charge process; \( a_1 \) and \( b_1 \) are balanced coefficient used to take into account the work conditions.

\[
SOC = C(t) / Cn_0 \tag{4}
\]

\[
C(t) = Q(t_0) - Qd(t) + Qc(t) \tag{5}
\]

\[
Qc(t) = [b_1(SOC) \times b_2(Qd) \times |I_{bat}(t)| \times dt] \tag{7}
\]

\[
Qd(t) = [a_1(I_{bat}) \times a_2(T) \times |I_{bat}(t)| \times dt] \tag{6}
\]

The coefficient \( a_1 \) is function of the discharge current in the battery and of the reference current \( I_0 \) corresponding to the reference capacity \( Cn_0 \). It permits to calculate the equivalent charge quantity extract of the battery during discharge process with the equivalent reference current \( I_e \) whatever the current rate \( I_{bat} \). It corresponds to the Peukert equation where \( n \) is the Peukert coefficient.

\[
a_i = (I_{bat}(t) / I_0)^{(n - 1)} \tag{8}
\]

The Peukert coefficient depends of the current rate and is generally in the range 1.2-1.6. Values of \( n \) is given by Table 2 as a function of the current \( I_{bat}(t) \).

The coefficient \( a_2 \) is used to take into account of the temperature effect. It is a function of the reference temperature \( T_{ref} \) equal to 20°C and the ambient temperature \( T_{amb} \). A corrective factor of 0.75% is introduced from the French policy NF C58-510 on lead acid batteries for solar application.

\[
a_2 = 1 / (1 + 0.0075 \times (T_{amb}(t) - T_{ref})) \tag{9}
\]

The coefficient \( b_1 \) is an innovate point in the SOC estimation. It permits to take into account the influence of the last discharge on the next charging process. \( b_2 \) correspond to the rate between the equivalent quantity of charge extract from the battery during discharge process calculated with equivalent coefficients \( a_1 \) and \( a_2 \) (= Qd), and the same variable calculated without the equivalent coefficient.

\[
b_2 = Qd / [I(I_{bat}) \times dt] \tag{11}
\]

This coefficient allows to maintained feasibility of calculi during irregular cycling process such as in photovoltaic application.

4. Optimisation algorithm
The objective of the power system is to supply loads with the least cost while satisfying the constraints imposed. The problem will be solved with hourly step size. Equations (18) and (19) show the constraint imposed on batteries on SOC and batteries power $P_{bat}$.

\[
0.2 < \text{SOC} < 0.9 \\
P_{bat} \leq 2 \text{ kW}
\]  

(18)  

(19)

Referring to fig. 2, the algorithm has to find the batteries and grid power schedule which satisfy the objective function along the entire simulation period. We define below calculations of decision variable energy cost and cost functions used by the algorithm to find the optimal power flow solution. The problem is formulated based on the discretization of a 24 hours future prediction horizon with a step size of one hour [6].

All the conceivable power flow directions in the system are taken into account. Each one is optimal for a particular range value of the decision variable.

At each discrete time instance, from real time and predicted values of solar power availability, loads consumption and batteries SOC, the algorithm calculates the decisions variables and applies the corresponding optimal power flow direction.

4.1. Energy cost

Because we want to supply loads with the least cost, we need to estimate energy cost of each source. This subsection presents the method to obtain energy cost of the photovoltaic generator and batteries.

Photovoltaic energy cost is obtained from equation 20.

\[
PV_{cost} = \frac{\text{Inv}_{pv}}{Y_{pr} \times \text{Life}_{pr}}
\]

(20)

With:

$\text{Inv}_{pv}$ = Grid connected photovoltaic system investment cost (€/kWp). From [7], this value is assumed to be equal to 6000 €/kWp in France.

$Y_{pr}$ = Annual photovoltaic yield (kWh/kWp). From experimental measures, this value is assumed to be equal to 1200 kWh/kWp in France.

$\text{Life}_{pr}$ = Life time of the photovoltaic generator (years). This value is estimated to 20 years.

So the photovoltaic energy cost is:

\[
PV_{cost} = 0.25 \text{ €/kWh}
\]

(21)

Batteries energy cost is composed of two terms, the discharge energy cost and the charge energy cost. The discharge energy cost $Bat_{dch\_cost}$ (€/kWh) is a constant obtained from equation (22).

\[
Bat_{dch\_cost} = \frac{\text{Inv}_{bat}}{N_{ref} \times DOD_{ref}}
\]

(22)

With:

$\text{Inv}_{bat}$ = Batteries investment cost (€/kWh). Taking into account the future cost reduction achieved by the massive employment of grid couple storage system, this value is estimated to 100 €/kWh for lead acid technology.

$N_{ref}$ = Reference cycle life of batteries (number of cycle). It is assumed to be equal to 1000 for a reference depth of discharge of 80%.

$DOD_{ref}$ = Reference depth of discharge of batteries (%). It assumed to be equal to 80%.

So the discharge energy cost is:

\[
Bat_{dch\_cost} = 0.12
\]

(23)

Charge energy cost $Bat_{ch\_cost}$ (€/kWh) is the energy price of the source used to charge batteries divided by the batteries charge efficiency $eff_{bat}$ estimated to 0.85. If batteries are charge with PV, this quantity is equal to $PV_{cost}$, if it is charge with the grid, it corresponds to energy price from the grid (24).

\[
Bat_{ch\_cost} = \begin{cases} 
PV_{cost} / eff_{bat} & \text{if charged from PV} \\
grid\_cost / eff_{bat} & \text{if charged from grid}
\end{cases}
\]

(24)

The batteries energy cost $Bat_{cost}$ (€/kWh) is the sum of the charge and discharge energy cost (25).

\[
Bat_{cost} = Bat_{dch\_cost} + Bat_{ch\_cost}
\]

(25)

4.2. Cost functions

The optimum power direction is chosen in function of the cost function results. Two cost functions are defined ($Present\_cost\_fct$ and $Future\_cost\_fct$) to choose the optimal state of batteries (charge ($P_{bat} > 0$), discharge ($P_{bat} < 0$) or idle ($P_{bat} = 0$)). $Present\_cost\_fct$ is defined as the difference between the grid cost and Batteries cost (24).

\[
Present\_cost\_fct = grid\_cost - Bat_{cost}
\]

(26)

It is calculated to estimate feasibility of batteries discharge operation (so when $P_{pv} < P_{load}$). If the $Present\_cost\_fct$ is positive, $grid\_cost$ is higher than $Bat_{cost}$, so discharge of batteries to supply loads is the least cost operation. Otherwise, loads are supply by the grid and batteries are in idle state.

In order to estimate feasibility of batteries charge operation, predictions are necessary. A prediction matrix has been developed containing the future loads power demand ($f_{P_{load}}$), future grid electricity price ($f_{grid\_cost}$ (€/kW)), and future PV power availability ($f_{P_{pv}}$ (kW)). The algorithm finds into the prediction matrix the periods when PV power is not enough to supply loads. It reads the future grid electricity price at this time and compares it to the battery energy cost calculated as a function of the charge source. The future cost function $Future\_cost\_fct$ is defined as the difference between the future grid electricity price, gains from purchase PV power $PV_{gain}$ (€/kWh), and the batteries cost (25).

If PV modules are the batteries charge source (so when $P_{pv} > P_{load}$), we have to submit to the future electricity price the gain obtained by selling PV power to the grid instead of charging batteries. By this way, we can decide at any moment if it is cheaper to charge batteries or to feed the grid. If PV modules are not the charge source, it means PV power is equal to zero, so $PV_{gain}$ is zero.

\[
Future\_cost\_fct = f_{grid\_cost} - PV_{gain}
\]
If battery energy cost is lower than the future grid electricity price, batteries are charged from the corresponding source; otherwise, batteries are not used. By this way, batteries charge is anticipated to supply loads when PV power is not enough.

5. Simulations results

Two hypotheses have been assumed during simulations. Firstly, the power flow from batteries to the grid is not considered in our algorithm. Secondly, we assumed that predictions are perfect. This means that the true values of variables match exactly with the predictive values. This situation is not realistic but simulations with perfect predictions are necessary to study the algorithm behaviour in optimal conditions.

Figure 3 and Figure 4 show the results of the optimisation algorithm for the 13 of July 2007.
As expected, batteries are charged with the grid during low price periods and are discharged to supply the loads during PV unavailability and high prices periods. The maximum battery power is respected and its SOC is kept in the range allowed. The total energy spent during simulation is obtained with equation (28). $E_i$ (kW) is the energy quantity from the source $i$ (PV, grid or batteries) and $E_i\_cost$ (€/kWh) is the price of the energy from the source corresponding to the power $E_i$.

Money spent = $\sum(E_i \times E_i\_cost)$  \hspace{1cm} (28)

The total money spent during on day is equal to 10 €. This is less than the money spent using only the grid as power source, which is equal to 15 €. The annual benefits from the system are equal to 1825 €. In this economical context, the algorithm assures to supply loads at the least cost and reduce electricity cost.

6. Conclusion

Energy storage associated to grid connected PV systems enables an optimal control and use of solar power. The algorithm developed in this paper assures loads supply at the least cost over the entire period studied. The algorithm determines for any moment the power flow in the system. It takes into account the real time and predictive values of loads demand, electricity grid prices, batteries SOC and solar power availability. A significant value of money is saved from the system use.

Simplicity of the algorithm developed enables to implement it easily into a microprocessor in order to develop an experimental energy management system which will be tested at INES institute in Chambéry.

7. References


