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Sensitivity analysis for photovoltaic water pumping systems: Energetic and economic studies

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A B S T R A C T

In agricultural remote areas where electrical energy is required to supply water pumping plants, photovoltaic modules are considered a good option to generate electricity. The reliability of autonomous Photovoltaic water pumping plants depends essentially on the system components size, which should meet the criteria related to the plant autonomy and the water volume required for irrigation. In this context, this research paper proposes an approach to size the elements of an autonomous photovoltaic system equipped with an energy storage device (a battery bank), and which is used to supply a water-pumping plant with electricity. The proposed approach determines the optimal surface of the photovoltaic modules, the optimal capacity of the battery bank and the volume of the water storage tank. The optimization approach takes into account the monthly average solar radiation, the fulfillment of the water needed for the crops' irrigation and the number of the days of autonomy. Measured climatic data of 10 ha situated in Northern Tunisia and planted with tomato are used in the optimization process, which is conducted during the tomato vegetative cycle (from March to July). The optimal results achieved for this farm are 101.5 m^2 of photovoltaic modules' surface, 1680 A h/12 V of the battery bank and 1800 m3 of the volume of the water storage tank. Then, to verify the reliability of the proposed optimization approach, the results of the proposed sizing algorithm are compared with those of a commercial optimization tool named HOMER, which shows better results using the proposed approach. Finally, the economic reliability of the obtained size is studied and compared with systems that include a diesel generator, and a diesel generator- photovoltaic panels, respectively, using climatic and economic parameters in three countries: Tunisia, Spain and Jordan. The economic analysis for these water pumping systems showed that photovoltaic- batteries/Pump system is the optimum solution in the three countries. However, the initial cost of the system can be recuperated faster in Spain than in Tunisia and Jordan due to high prices of the diesel these two countries.

1. Introduction

For remote agriculture areas, it is common to use diesel generators to supply autonomous installations. However, due to the instability of the diesel cost and the decrease in the photovoltaic (PV) technology costs, PV- batteries systems are best placed to generate electricity especially in these areas, where the continuous need for providing diesel is considered the most important disadvantage of systems that use diesel generators to generate electricity. Therefore, this renewable based solution should be reliable and economic. Thus, sizing and the energy optimization of PV- batteries installations must be properly performed, since they are affected especially by the energetic and climatic constraints, namely the intermittence of the climatic parameters [1,2].

In fact, sizing of autonomous PV systems is considered a key factor that allows the PV energy generated to be optimized and the electrical power required to the loads supply to be produced during the needed days of autonomy [2,3]. Consequently, the optimal sizing is indeed recognized as being crucial for the system to provide satisfactory power to the loads. More precisely, for agricultural applications, where water is used principally for crops irrigation, the size of PV- batteries systems must guarantee the water volume needed during the crops vegetative cycle [3]. In fact, the knowledge of the water volume required, the site' climatic parameters, the PV module and the batteries characteristics are crucial for the autonomous system design [1,2]. Indeed, sizing optimiza-

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Nomenclature

A_{c_i} amount of clouds per day (%)
ANN Artificial Neural Network
C_b battery cost (€/battery for n_y)
C_{bat} nominal battery capacity (A h)
C_{fuel} cost of the fuel (€/l)
C_{inv} cost of inverter (€/inverter for n_y)
C_{opt} optimum batteries' capacity (A h)
C_{oil} cost of engine oil (€/l)
C_p Peukert capacity (A h)
C_{pv} PV module cost (€/module for n_y)
C_R stored charge in the battery (W h)
C_{diesel} diesel generator price (€)
$\cos t_{s1}$ system 1 cost (€)
$\cos t_{s2}$ system 2 cost (€)
$\cos t_{s3}$ system 3 cost (€)
d_{aut} number of days of autonomy
d_{rech} number of days needed to recharge the battery
dod depth of discharge
E_c energy stored in the batteries (W h)
E_d daily energy consumption (W h)
E_e energy extracted energy from the batteries (W h)
E_{pump} energy needed by the pump (W h)
E_{PM} energy extracted from the battery at pm (W h)
E_{PV} energy generated by the PV modules (W h)
EC_e crop salt tolerance (dS. m^{-1})
EC_w electrical conductivity of the irrigation water (dS. m^{-1})
ET_o reference crop evapotranspiration
f_i: irrigation frequency
G solar radiation (W/m^2)
GA genetic algorithm
H monthly global solar radiation (W/m^2)
$\overline{H}$ solar energy for the month M (W h/m^2)
$H_b(t,d)$ direct solar radiation
$H_d(t,d)$ diffused solar radiation (w/m^2)
$H_t(t,d)$ solar radiation on the tilted module (W/m^2)
$I_{bat_{(k)}}$ battery bank current considered constant (A)
K correction factor
k_c seasonal crop coefficient
k_p Peukert coefficient
k_t clearness index
l_f leaching efficiency coefficient as a function of the irrigation water applied (%)
L_R leaching fraction given by the humidity that remains in the soil expressed in (%)
LLP loss of Load Probability
M month of the year
M_{bat} maintenance cost for one battery (€/battery per year)
M_{chop} maintenance cost for one chopper (€/chopper per year)
M_{diesel} diesel generator maintenance cost (€)
M_{inv} maintenance cost for one inverter (€/inverter per year)
M_{pv} PV module maintenance cost (€/module per year)
MPPT maximum power point tracking
n_{bat_i} minimum batteries number
n_{bat_M} battery number in the month M
$n_{bat_{opt}}$ optimum batteries number using the sizing algorithm
n_{bat} batteries number
n_c number of consecutive cloudy days
n_{c_i} number of consecutive cloudy days per month M
n_{chop} number of choppers
n_{diesel} number of diesel engines used
n_{M_i} days number in the month M
n_{oil} number of oil changing times by year
n_{pv} number of PV modules
n_y years number used for the systems costs evaluation
NOCT Nominal Operating Cell Temperature
PV photovoltaic
P_{pv} photovoltaic power (W)
r_m the rainfall (m^3)
R_s series resistance of the PV module (Ω)
R_p parallel resistance of the PV module (Ω)
R'_b ratio of direct radiation on tilted PV module and direct radiation on horizontal PV module
P_{pump} water pump power (W)
P_{pvi} PV module power (W) at the minimum module surface S_i
S PV module surface (m^2)
S_i minimum PV modules' surface (m^2)
S_M PV module surface at month M (m^2)
S_{opt} optimum module surface (m^2)
T mean monthly air temperature
T_a ambient temperature at the panel surface (°C)
T_{aref} reference ambient temperature (°C)
$T_c(t)$ PV cell temperature (°C)
T_{ref} PV cell reference temperature (°C)
V water volume needed to irrigate Tomatoes
V_{bat} battery voltage (V)
V_{fuel} volume of fuel consumption (l/h)
$V_{leaked/excess}$ water volume leaked or in excess (m^3)
V_{pumped} possible pumped water volume (m^3)
$V_{reservoir}$ required volume of the reservoir (m^3)
w angle of the sun at a specific hour
W_{pv} average daily radiation (W h/m^2/day)
W_{pvc_i} solar energy for the month M using the clear sky model (W h)
w_s angle of the sun at sunset
y_{bat} number of times the batteries are replaced during n_y years
y_{chop} number of times the chopper is replaced during n_y years
y_{inv} number of inverters replaced during n_y years
η efficiency coefficient required (%)
η_{bat} electrical efficiency of batteries bank (%)
η_{error} error permitted in the sizing approach (%)
η_{inv} inverter performance (%)
η_l electrical efficiency of installation that includes Ohmic-wiring losses (%)
$\eta_{matching}$ PV module matching performance (%)
η_{opt} PV module performance due to optical effects (%)
η_{pv} PV module yield (%)
η_r module efficiency at the reference conditions, STC (Standard Test Conditions) (%)
η_{reg} regulator performance (%)
$\eta_{reservoir}$ water losses in the reservoir (%)
η_1 efficiency coefficient obtained (%)
β PV module tilt angle (°)
β_{pv} temperature coefficient for the module yield ($^{\circ -1}$)
ρ Albedo of the soil
∂k time between instant $k-1$ and k
θ incidence angle of the solar radiation (°)
θ_z Zenith angle of the sun (°)
$\Delta dod_{\max}$ maximum dod variation (%)
Δt pumping duration (h)
Δt_{diesel} time duration of operation (h/day)