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 m² 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.

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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-
Nomenclature

A
c
ANN
C
battery charge cost (€/battery for \( n_p \))
Cn nominal battery capacity (A h)
Cfuel cost of the fuel (€/l)
Cinv cost of inverter (€/inverter for \( n_p \))
Copt optimum batteries' capacity (A h)
Coil cost of engine oil (€/l)
Cp Peukert capacity (A h)
Cpvm PV module cost (€/module for \( n_p \))
Cr stored charge in the battery (W h)
C
diesel generator price (€)
Cos.system 1 cost (€)
Cos.system 2 cost (€)
Cos.system 3 cost (€)
daut number of days of autonomy
dtech number of days needed to recharge the battery
dod depth of discharge
Ec energy stored in the batteries (W h)
Ed daily energy consumption (W h)
Ee energy extracted from the batteries (W h)
Efp energy needed by the pump (W h)
Em energy extracted from the battery at pm (W h)
Ep energy generated by the PV modules (W h)
Ecrop salt tolerance (dS. m\(^{-1}\))
Ecw electrical conductivity of the irrigation water (dS. m\(^{-1}\))
Ets reference crop evapotranspiration
f
t irradiation frequency
G solar radiation (W/m\(^2\))
GA genetic algorithm
H monthly global solar radiation (W/m\(^2\))
Hs solar energy for the month M (W h/m\(^2\))
Hs(t, d) direct solar radiation
Hd(t, d) diffuse solar radiation (W/m\(^2\))
H(t, d) solar radiation on the tilted module (W/m\(^2\))
Ibat,ref battery bank current considered constant (A)
k correction factor
k
seasonal crop coefficient
kp Peukert coefficient
kt clearness index
leaching efficiency coefficient as a function of the irrigation water applied (%)
Lr leaching fraction given by the humidity that remains in the soil expressed in (%)
LLP loss of Load Probability
t month of the year
Mbat maintenance cost for one battery (€/battery per year)
Mchop maintenance cost for one chopper (€/chopper per year)
Mdiesel
diesel generator maintenance cost (€)
Minv maintenance cost for one inverter (€/inverter per year)
Mpv PV module maintenance cost (€/module per year)
MPPT maximum power point tracking
nbat minimum batteries number
nbat month battery number in the month M
nbat opt optimum batteries number using the sizing algorithm
nbat batteries number
nt number of consecutive cloudy days
nt number of consecutive cloudy days per month M
nchop number of choppers
ndiesel number of diesel engines used
N days number in the month M
nool number of oil changing times by year
nps number of PV modules
nyears number used for the systems costs evaluation
NOCT Nominal Operating Cell Temperature
PV photovoltaic
Ppv photovoltaic power (W)
Rm the rainfall (m\(^3\))
Rb series resistance of the PV module (Ω)
Rd parallel resistance of the PV module (Ω)
Rd ratio of direct radiation on tilted PV module and direct radiation on horizontal PV module
Ppump water pump power (W)
Pfuel PV module power (W) at the minimum module surface
S PV module surface (m\(^2\))
Sm minimum PV modules' surface (m\(^2\))
Sopt optimum module surface (m\(^2\))
T mean monthly air temperature
Tamb ambient temperature at the panel surface (°C)
Tref reference ambient temperature (°C)
Tcell PV cell temperature (°C)
Tref PV cell reference temperature (°C)
V water volume needed to irrigate Tomatoes
Vbat battery voltage (V)
Vfuel volume of fuel consumption (l/h)
Vleaked/excess water volume leaked or in excess (m\(^3\))
Wpumped possible pumped water volume (m\(^3\))
Vreservoir required volume of the reservoir (m\(^3\))
w angle of the sun at a specific hour
WP average daily radiation (W h/m\(^2\)/day)
Wp INCLUDING solar energy for the month M using the clear sky model (W h)
wss angle of the sun at sunset
ybat number of times the batteries are replaced during \( n_y \) years
ychop number of times the chopper is replaced during \( n_y \) years
ynpv number of inverter replaced during \( n_y \) years
\( \eta \) efficiency coefficient required (%)
\( \eta \)| efficiency coefficient (%) of the PV module under standard test conditions (STC)
\( \eta \) electrical efficiency of batteries bank (%)\( \eta \) error permitted in the sizing approach (%)\( \eta \) error inverter performance (%)
\( \eta \) electrical efficiency of installation that includes Ohmic-wiring losses (%)\( \eta \) module matching performance (%)\( \eta \) module efficiency at the reference conditions, STC (Standard Test Conditions) (%)\( \eta \) water losses in the reservoir (%)\( \beta \) temperature coefficient for the module yield (°C-\(^{-1}\))\( \rho \) Albedo of the soil\( \delta k \) time between instant \( k - 1 \) and \( k \)\( \theta \) incidence angle of the solar radiation (°)\( \theta \) Zenith angle of the sun (°)\( \Delta \) maximum dod variation (%)\( \Delta t \) pumping duration (h)\( \Delta t \) time duration of operation (h/day)
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