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Energetic and economic sensitivity analysis for photovoltaic water pumping systems

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ABSTRACT

Costly battery energy storage are used in photovoltaic water pumping systems to ensure the power supply continuity and the system autonomy. However, the question of designing an optimum, economic and reliable system has not been fully answered. This research work proposes a smart sizing approach of a photovoltaic water pumping system components destined to Tomatoes irrigation. The system elements sizes namely the photovoltaic modules' surface, the battery bank capacity and the reservoir volume, are designed to save energy generated in excess, supply the water pump and ensure the system autonomy. Fluctuations occurrence, number of successive cloudy days and energetic losses are taken into account when designing. A theoretical analysis was carried out to assess the relation between the photovoltaic modules surface, the battery bank capacity and the water volume needed for the crops irrigation during the crops' vegetative cycle (from March to July). Additionally, the sizing algorithm results have been validated using PVsyst tool, which shows the efficiency of the obtained sizing. The economic sensitivity analysis for these water pumping systems in three countries, which are Tunisia, Spain and Qatar showed that photovoltaic-batteries/pump system shows that these systems are reliable and economic for both developing and developed countries.

1. Introduction

The need to save water and energy is a serious issue that has increased in importance over the last years and will become more important in the near future (Young, 2013; Damerau et al, 2016; Yahyaoui et al, 2016). The low price of fuel was the reason why renewable energy sources are not widely used in several applications, including water pumping. Thus, water pumping systems based on renewable energies are still scarce, even though they have clear advantages, namely, low generating costs, suitability for remote areas, and being environmentally friendly. Nowadays, the price of electric energy is rising constantly, investing in more efficient solutions is also increasing (Ramos and Ramos, 2009).

Some renewable energies have been used in water pump applications, especially in remote agricultural areas, thanks to their potential. The renewable energies use depends on the user propensity to invest in renewable based pumping systems, his/her awareness and knowledge of the technology for water pumping, and also on the availability, reliability, and economics of conventional options (Demetrios and Sotirios, 2006). Moreover, the evaluation of the groundwater volume required for irrigation and its availability in the area are also relevant in determining the profitability of renewable energies.

In this context, the Photovoltaic (PV) energy is considered an attractive solution to provide autonomous water pumping systems with electricity, especially in remote areas, where the continuous need to provide diesel is considered the most important disadvantage of diesel based systems. Therefore, the PV system should provide the autonomous installation with the needed energy, which requires an optimum sizing and energy management of the system components that are affected by the intermittent climatic parameters, namely the solar radiation and the ambient temperature (Yahyaoui, 2016; Yahyaoui et al. 2016).

In fact, the components sizing of autonomous PV systems is considered a key factor to generate the required power by the water pump during the days of autonomy (Jakhrani et al., 2012; Khatib et al., 2013). Consequently, the optimal sizing is indeed

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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_{inv}	cost of inverter (€/inverter for n_y)
C_{opt}	optimum batteries' capacity (Ah)
C_p	Peukert capacity (A h)
C_{pv}	PV module cost (€/module for n_y)
C_R	stored charge in the battery (W h)
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)
$\bar{H}$	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)
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_{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_{M_i}	days number in the month M
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'_b	ratio of direct radiation on tilted PV module and direct radiation on horizontal PV module
P_{pump}	water pump power (W)
$P_{pv\,i}$	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)
$T_{a\,ref}$	reference ambient temperature (°C)
$T_c(t)$	PV cell temperature (°C)
T_{ref}	PV cell reference temperature (°C)
t_{sr}	time of sunrise (h)
t_{ss}	time of sunset (h)
V	water volume needed to irrigate Tomatoes
V_{bat}	battery voltage (V)
$V_{leaked/excess}$	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 (°C^{-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)

recognized as being crucial for the system to provide satisfactory power to the load. More precisely, for agricultural applications, where water is used principally for crops irrigation, the size of PV modules surface, the battery bank capacity and the reservoir volume must guarantee the pumping of the water volume needed by the crops during their vegetative cycle (Khatib et al., 2013).

In previous works, procedures have been proposed to size the PV water pumping components by taking into account energetic criteria (Capizzi et al., 2011; Acakpovi et al., 2012; Khatib et al., 2012). In this context, several techniques have been used in the literature. While early studies focused on developing analytical methods based on a simple calculation of the PV modules' surface