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A unified approach for designing a photovoltaic solar system for the underground water pumping well-34 at Disi aquifer

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ABSTRACT

This paper aims to present a detailed design of a standalone photovoltaic system used to power continuously a submersible water pump from a selected well (Well-34 of a current static water level, SWL = 147.3 m), out of 55 production wells located at the Disi aquifer, where each of these wells should have a continuously-operating water flow rate of 80 l/s (288 m^3/h) according to the Disi project specifications. Initially, solar irradiation calculations on horizontal and tilted surfaces were carried out to identify the potential of solar energy available in kW h/m^2/day in the Disi aquifer. Then, a system design approach based on the worst month of the year (December) was carried out to choose and size the components of photovoltaic system that is required to operate the submersible pump over the 25-year operation period. The system sizing implies defining the number and type of solar panels required to capture the available solar energy, the capacity and number of batteries, inverter rating, cable sizing, charge controller numbers and rating to ensure the maximum reliability of the system. Furthermore, beyond the design conditions of the worst month (December), extra energy can be produced by the PV system during the rest of the year time, which can be used for many purposes. Also, the design process considers the problem of dust accumulation on PV surfaces and this can be dealt with by periodic cleaning.

1. Introduction

1.1. General overview of the Disi project

The Disi-Mudawara to Amman Water Conveyance Project is a water supply project currently under construction in Jordan. It is designed to pump almost 100 million m^3/year from all 55 wells (almost 250 m^3/h from each well for 24 pumping hours per day) with an average manometric head of 190 m) from the Disi aquifer, which lies beneath the desert in southern Jordan and northwestern Saudi Arabia. The proposed pump type to be used is a 14″ turbine submersible pump (installed in an 18 5/8″ well casing) with an estimated motor size of 150–250 kW for each well pump and the water is to be pumped to Amman through 1.5 m diameter pipes. Construction began in 2009 and is expected to be completed during 2013 with a total cost of JD 1.2 billion. The water in Disi aquifer is classified as a fossil aquifer. At the extraction rate mentioned earlier, the water in the aquifer will last for almost 50 years, according to the Disi Water Company (DIWACO) that is supervising the whole project. Only a small portion of the Disi aquifer lies beneath Jordan, while the majority lies beneath Saudi Arabia, Allen [1].

This project is expected to cover the increasing demand of water in Amman which recently reached 90 million cubic meters per year, Raddad [2]. As proposed by the Jordanian government, the 100 million cubic meters per year will be pumped from 55 production wells drilled in the aquifer. However, a total of 64 wells will be drilled; the extra wells are to be used as piezometers to measure the elevation of water. The wells producing water are being drilled by Site Drilling Co. to a total depth of 500–550 m, while the piezometers were drilled to, more or less, 400 m. After being pumped from the wells, water will then be transported to Amman, via a 325 km pipeline, passing through a pumping station, and then flowing by gravity till being pumped up again. The reservoirs near Amman are only 200 m higher than the surface area where the pumping field is located.

The project is funded on a build-operate-transfer concession contract between the Jordanian government and the Disi Water Company (DIWACO), a subsidiary of the Turkish construction company GAMA Energy, which is partially financing the project with

Abbreviations: AH, Ampere Hour; B, Battery; C, Controller; CEC, California Energy Commission; DD, Drawdown; PV, Photovoltaic; DC, Direct Current; DOD, Depth of Discharge; LCC, Life Cycle Cost; LCCA, Life Cycle Cost analysis; MWM, Method of the Worst Month; PMDC, Permanent Magnet DC Motor; PSH, Peak Sun hours; STC, Standard Test Conditions; SWL, Static Water Level; THP, Total Pumping Head; UWSC, Universal Wire Sizing Chart; VDI, Voltage Drop Index.

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Nomenclature

A_{array}	area required by the PV panel (m^2)
A_{module}	area required by the PV module (m^2)
$A_{spacing}$	area spacing between required PV panel (m^2)
C_P	Temperature coefficient of maximum power (%/°C)
F_T	cable temperature factor
G_{sc}	solar constant (W/m^2)
H_{STC}	peak sun irradiation (W h/m^2)
H_0	daily extraterrestrial radiation on a horizontal surface (MJ/m^2)
$\bar{H}_T$	monthly average daily radiation on tilted surfaces (MJ/m^2)
$\bar{H}_{bT}$	monthly average daily beam radiation on a tilted surface (MJ/m^2)
$\bar{H}_b$	beam radiation (MJ/m^2)
H_d	monthly-averaged daily diffuse radiation on a horizontal surface (MJ/m^2)
$\bar{H}$	monthly-averaged daily radiation on a horizontal surface (MJ/m^2)
$\bar{H}_{T,\max}$	monthly-highest radiation value (MJ/m^2)
I_T	hourly total irradiance (kW h/m^2)
I	total adjusted current through cable (A_{DC})
$I_{Battery}$	DC current of the battery (A_{DC})
I_{SC}	short circuit DC current (A_{DC})
$I_{inv,in}$	inverter's input DC current
K_T	monthly average clearance index
L_T	temperature loss factor
L_C	cable loss factor
L_B	battery loss factor
L_M	mismatch loss factor
L	total length of cable (ft)
N	number of daylight hours
N_a	days of autonomy
n	day of the year (i.e. n = 1 for January 1, n = 32 for February 1, etc.)
$NOCT$	nominal operating cell temperature (°C)
$P_{\max}$	maximum rated power of PV module (W_p/m^2)
$P_{m,max}$	maximum rated power of motor pump (kW)
$P_{\max,actual}$	actual produced DC power by A single PV panel (kW)
$P_{T,loss}$	power loss (kW)
$P_{inv,in}$	power input of the inverter (kW)
$\bar{P}_m$	motor power (kW)
$\bar{R}$	ratio of $\bar{H}_T$ to $\bar{H}$
R_b	ratio of H_{bT} to H_b
T_m	average module temperature (°C)
T_a	average ambient temperature (°C)
$T_{m,ref}$	reference module temperature (°C)
V	operating voltage (V_{DC})
V_{Bat}	rated battery voltage (V_{DC})
V_{sys}	rated system voltage (V_{DC})
V_{MP}	maximum power voltage (V_{DC})
D_v	permissible voltage drop (use no. only (%)
Y	shading distance (m)
X	height of titled PV panel (m)
a	solar altitude at certain solar time (°)
β	tilt angle (°)
γ	azimuth angle (°)
δ	declination (°)
ω_s	sunset hour angle (°)
ω_s'	sunset hour angle for tilted surfaces (°)
ϕ	latitude angles (°)
ρ	ground Albedo or ground diffuse reflectance
$\eta_{inv,CEC}$	CEC weighted efficiency of inverter

General Electric Inc. Project owners are going to profit back through selling Disi water to the people of Amman for the next 25 years, and then hand the wells to the Jordanian government.

1.2. Problem definition

Major conventional sources for powering underground water pumps are either fossil fuel generators or electricity from a nearby grid. Both methods have considerably expensive running costs, and varying implementation costs depending on the location, nature and budget of the water project. The choice of solar PV underground water pumping concept over conventional means of energy is gaining more and more popularity around the world, especially where electricity is either unavailable or unreliable.

Since the project is located in the farthest south of Jordan next to Wadi-Rum and requires about 13 MW for all 55 wells, then implementation of an electrical grid will be difficult and very costly due to the hard desert terrain and the distant wells, which cover a circular area of 40 km or more in diameter. The use of Diesel generators will be also very expensive on a life cycle cost basis due to costs of fuel, maintenance and operation. And because of the high solar irradiation levels in Disi area and the high number of shiny days throughout the year, solar water pumping through the use of off-grid photovoltaic panels' electricity could be an efficient-cost effective method for the long-life water supply.

1.3. Project outline

The main aim of this work is to choose and size the main components of a standalone PV system to power continuously the submersible pump at the selected well-34 as illustrated in Fig. 1. The configurations showed in Fig. 1 that PV arrays are connected in series to produce 550 V DC input while they are connected in parallel with controllers and batteries. It should be noted here that a string of controllers should be connected in series to produce the required 550 DC input to the inverter. According to Disi project specifications, the motor powers for the well pumps (250 kW each) were already selected of the submersible type. Pump selection depended upon specific application requirements and cost considerations. For this study purposes, system flow and head requirements of the selected well-34 are to be determined and checked to verify the actual pump selection. This work shows that large stand alone PV systems (13 MW) for such large project can be designed and carried out.

1.4. Study methodology

The work began with collection of detailed weather data for the area of Disi including temperature, weather status, estimated number of sunny days and the wind speed. The technical data for water pumping requirements were then investigated over the project's period, which was assumed to last for 25 years, and the motor power versus water drawdown relationship was illustrated to check the suitability of the suggested submersible water pump selected by the Disi project technical team. And accordingly, the DC–AC inverter was sized and selected. Levels of solar irradiation in the Disi area were carefully studied, calculated and compared to international solar databases. Based on this data, the PV array was sized and type of PV panels was selected, and that was followed by the sizing and selection of batteries, charge controllers and connecting cables.