Electrical Power Quality Analysis and Hydraulic Performance for Photo Voltaic Surface Water Pumping Unit

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Abstract: Photovoltaic now used in new irrigation system as a source of renewable energy to run the pumps. It’s can be used in remote areas, which it’s very difficult and more expensive to establish power stations or to install transmission lines to connect these areas with the electrical grid. Surface pump can be used in modern irrigations systems and connected to PV power supply to save energy and water. In this paper a system contains 10 hp surface pump and 15 kW PV system uses to drive the pump unit are studied. The paper investigates mathematical models for surface PV pumping system component. The performance of this system is studied by using this mathematical model during a long time, and the effect of solar radiations values on the system performance is estimated. The paper introduced a simulations and experimental results of the PV pumping in daily hourly average during one year. A good agreement between the simulations results and experimental results are found. The paper investigates the overall performance foxing on the water flow rate values obtained from the unit during one year. Also the electrical power quality analysis of the AC voltage feeds for the pump unit are measured and calculated. Due to solar radiations variation during day hours, and during different months the electrical performance such as; voltage current, power and also harmonic contents is changed depends on the values of solar radiations. The electrical signals and power quality are measured on the field by using power quality devices in different days and statues of operations. The results showed that, during low radiations periods the voltage and frequency are varied in a constant relation to reduce the pump speed and hence reduce the water flow rate to be proportional to input energy come from the PV panels. In case of high solar radiations the inverter runs the pump at constant frequency values depend on pump specifications. And during clouds occurred the system is stopped.

Keywords: Power Quality Analysis, Surface Pump, Photovoltaic, Hydraulic Performance

1. Introductions

Egypt is located in a semi-arid climatic zone characterized by hot, dry summers and temperate winters with limited rainfall. The Nile River is the almost exclusive source of freshwater to meet all needs; agricultural, industrial and domestic. Egypt is facing increasing demand for water from these sectors at a time when supply is fully allocated: Egypt’s share of water from the Nile has been fixed at 55.5 billion m$^3$ per year since the 1959. Agricultural production in Egypt occurs exclusively in the Nile Delta and a narrow corridor along the Nile River [1]. The agricultural sector is the largest user of water in the Egyptian economy, as crop production is entirely dependent on irrigation. Water is diverted from the Nile into the main (primary) canals, before passing into the branch (secondary) canals. Water from the branch canals is subsequently distributed to farmers via tertiary canals (mesqas), usually located below ground level, from where it is lifted to irrigated fields. The agricultural sector is now facing an energy crisis, as increasing electricity demand from urban areas is resulting in frequent shortages and blackouts. In addition, the Government of Egypt is controlling subsidies for fuel, and the cost of pumping is set to change. A low-cost, sustainable source of energy is required for farmers to continue pumping water for irrigations purposes. So it’s very important to use renewable energy sources such as solar and wind. In Egypt, it can be use solar-powered water lifting for irrigation, with the use of solar panels covering irrigation canals thereby also reducing evaporation losses. This system can provide sustainable source of energy for the lifting of
irrigation water and reduces evaporation losses from irrigation canals, thus increase efficiency and strengthen local capacities in Egypt to adopt, operate and maintain new techniques for the lifting of irrigation water from canals.

1.1. Solar Energy Applications for Water Pumping

Photovoltaic (PV) water pumping is one of the most typical PV applications in developing countries and has the potential to become a major force for social and economic development [1]. Many remote villages in the world are not yet connected to the electric grid and face severe problems of water for drinking and irrigation purposes [1]. Designed and developed a solar photovoltaic pump operated drip irrigation system for growing plantations in and region considering different design parameters, like pumps size, water requirements, and the variation in the pressure of the pump due to change in irradiance and pressure compensation in the emitters [2]. Solar powered water pumping has the potential to bring sustainable supplies of potable water to millions of people in developing countries [3]. Performances of a photovoltaic pumping system based on an induction motor are degraded once insolation varies far from the value called nominal, where the system was sized [4]. Solar PV can provide cost effectively at least some proportion of energy needs. Benefits to implementing solar as a source of power for irrigation pumping include: Reduced bills for mains electricity and diesel, reduced connection and infrastructure costs when new power lines and rods can be avoided if fully replacing mains electricity, no noise, fumes or fuelling runs if replacing diesel, Scalable – additional panels can be added to increase output, Flexible – solar power can be integrated with mains electricity supply if desired, Low maintenance. Protection from rising energy costs. Sunshine is free so generating energy on farm reduces exposure to rising electricity and diesel prices [5]. Photovoltaic (PV) panels are often used for agricultural operations, especially in remote areas or where the use of an alternative energy source is desired. In particular, they have been demonstrated time and time again to reliably produce sufficient electricity directly from solar radiation (sunlight) to power livestock and irrigation watering systems. A benefit of using solar energy to power agricultural water pump systems is that increased water requirements for livestock and irrigation tend to coincide with the seasonal increase of incoming solar energy [6]. All energy forms derive directly or indirectly from solar energy. Crop drying, solar-thermal electric power generation, solar heat collection, and direct conversion of solar energy into electricity are direct forms. Solar energy can be directly converted into electricity using either thermoelectricity or PV cells. A PV pump is one of the most reliable technologies for pumping water from boreholes, rivers, lakes, shallow wells, and canals. Because of the PV array’s modularity, the pumps can be redesigned as the demand increases by changing the motor-pump subsystem as long as the whole yield is sufficient [7]. PV water pumping systems are becoming a preferred choice in regions where the whole yield is sufficient [8]. PV systems for the pumping of groundwater are also used in Upper Egypt, proving the cost of the water unit pumped by PV systems is significantly less than that pumped by diesel systems. Solar PV pumps are becoming a preferred choice in remote locations to replace hand-pumps, grid connected electrical pumps and diesel pumps. In such places, solar PV pumps are even viable economically in comparison to conventionally run pumps [9]. Solar water pumps offer Egyptians the opportunity to live in off-grid desert communities and have access to essential groundwater resources will help to pull population away from an overcrowded Nile and take advantage of the desert’s abundance of sun and soil. It will open up a chance for Egyptians to find a new ways of making a living without having to depend on an unreliable electrical grid [10]. The area of the PV array can be decided according to the required total quantity of daily water demand and the pump power [11]. The output power from the photovoltaic panels is proportional to the amount of the incidental solar radiation and photovoltaic cell temperature. The use of booster reflectors is a promising solution to raising the intensity of incidental irradiance on the PV panel surface [12]. A solar water pumping system is ideal in remote locations where grid electricity does not exist or it is cumbersome to carry in gasoline or diesel to feed a pump. The drawback of solar pumping systems is a lot low costly than fossil fuel or grid-based systems to establish [13].

1.2. Electrical Power Quality Analyses

Power quality means the status of voltage and current wave shape at different operating conditions. In PV system due to using of inverter there are many problems occurred due to poor power quality such as: voltage disturbances for example voltage surges and impulses, voltage sags; harmonic invasion, flickering, and PF quality. The Harmonics contents and total harmonic distortions (THD) can be calculated by measuring the voltage and current signal and their values represent the status of power quality. Harmonics have destructive effects like torque pulsation, acoustic noise and increase power losses [14]. Modern power quality analysis is being used to measure and calculate the harmonic contents such as: 3rd, 5th, 7th harmonics, and flickers and also calculate the THD.

1.2.1. Total Harmonic Distortion

The series of harmonic components that represent a distorted waveform are often described by the THD. THD can be calculated from the following equations

$$THD = \sqrt{\frac{\sum_{n=2}^{\infty} V_n^2}{V_1}}$$

Where: $n$ is an order of the harmonic; $V_n$ is the rms value of the fundamental voltage and $V_1$ is the rms value of the voltage...
The voltage distortion limits in IEEE519 are fairly straightforward, as shown in Table 1. There are only three levels recommended, depending on the voltage level.

| Bus voltage at PCC ($V_n$) | Individual harmonic voltage distortion (%) | Total Voltage Distortion – THD $\%$ |
|---------------------------|--------------------------------------------|----------------------------------|
| $V_n \leq 69$ kv          | 3.0                                        | 5.0                              |
| $69$ kv < $V_n \leq 161$ kv | 1.5                                        | 2.5                              |
| $V_n > 161$ kv            | 1.0                                        | 1.5                              |

1.2.2. Flicker Problem

The power supply network voltage varies over time due to disturbance that occurs in the processes of electricity generation, transmission and distribution [15]. High power loads that draw fluctuating current, such as large motor drives and arc furnaces, cause low frequency cyclic voltage variations that result in flickering of light sources which flickers cause significant physiological discomfort, physical and psychological tiredness, and even pathological effects for human beings. Also can cause problems with the stability of electrical devices and electronic circuits.

Flicker is expressed in terms of two parameters: short term flicker severity $P_{ST}$ normally fixed at 10 min, during which short-term flicker severity is assessed, and long term flicker severity $P_{LT}$ usually 2h, during which long-term flicker severity is assessed. The equations used to calculate flicker is explained in Eq.(2,3) [16]:

$$P_{ST} = \sqrt{0.0314 P_{0.3} + 0.0525 P_{1.3} + 0.0657 P_{3.3} + 0.28 P_{10.3} + 0.08 P_{50.3}}$$ (2)

$$P_{LT} = \frac{1}{N} \sum_{i=1}^{N} P_{ST}^2$$ (3)

where $N$ is the number of $P_{ST}$ periods within the observation time of $P_{LT}$. Measurements would be required to calculate the $P_{LT}$ (2h). In the following part, these parameters are denoted as $P_{0.3s}$, $P_{1.3s}$, $P_{3.3s}$ etc., while the subscript ‘s’ (e.g. $P_{1.3s}$, $P_{3.3s}$) indicates that averaging has been applied according to the following formulas:

$$P_{1.3s} = (P_{0.3s} + P_{2.3s} + P_{1.3s})/3$$ (4)

$$P_{3.3s} = (P_{2.2s} + P_{3.3s} + P_{4.3s})/3$$ (5)

$$P_{10.3s} = (P_{4.3s} + P_{8.3s} + P_{10.3s} + P_{17.3s})/3$$ (6)

$$P_{50.3s} = (P_{3.3s} + P_{50.3s} + P_{80.3s})/3$$ (7)

2. Simulations Performance of Surface PV Pump System

2.1. Mathematical Modeling of Surface PV Pumping Systems

The overall simulation models of PV pumping system are shown in Figure 1 the load is an induction motor connected directly to the PV system. The system uses an inverter to convert the DC voltage output from the PV array into AC voltage to drive the induction motor and pump unit. A maximum power point model is used to obtain the operating maximum voltage value at each radiation level. A weather model uses some parameters and equations including: the latitude, longitude, time, date, and array fixing angle, to calculate the solar radiations falls on the PV array. In the following parts simulations models for each part are introduce and the full system simulation model to find the system performance during one year is introduced also. Finally a comparison between experimental results and simulation results are introduces.

2.2. Solar Radiations Calculations

According to the following equations; (8) to (22); and by following the sequence shown in Figure 2 the solar radiations components; $I_p$, $I_b$, and $I_t$ can be calculated and the results during one year is shown in Figure 3.
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\[ \delta = 23.45 \sin \left[ 360 \left( \frac{n_d + 284}{365} \right) \right] \]  
\[ \omega = 15 \left( t - 12:00 \right) \]  
\[ \alpha_s = \sin \phi \sin \delta + \cos \phi \cos \delta \cos \omega \]  
\[ \sin \gamma_s = \cos \delta \sin \omega / \cos \alpha_s \]  
\[ \cos \theta = \sin \delta \sin (\phi - \beta) + \cos \delta \cos \omega \cos (\phi - \beta) \]  
\[ \cos \theta_2 = \sin \delta \sin (\phi) + \cos \delta \cos \omega \cos (\phi) \]  
\[ H_d = \frac{24}{\pi} I_{sc} \left( 1 + 0.033 \cos \frac{360L}{365} \left( \frac{\omega_s \sin \delta}{\cos \phi \cos \delta \sin \alpha_s} \right) \right) \]  
\[ H_a = \frac{H_s}{H_o} = a + b \frac{S}{S_{max}} \]  
\[ S_{max} = \left( \frac{2}{15} \right) \cos^{-1}(-\tan(\phi - \beta) \tan \delta) \]  
\[ I_s = \frac{\pi}{24} (aa + bb \cos \alpha) \cos \omega - \cos \theta_2 \left( \frac{S}{360} \right) \]  
\[ \omega_s = 0.409 + 0.5016 \sin(\omega_s - 60) \]  
\[ bb = 0.6609 - 0.4767 \sin(\omega_s - 60) \]

\[ \frac{I_d}{I_g} = 0.95 \left( K_t < 0.175 \right) \]  
\[ \frac{I_d}{I_g} = 0.9698 + 0.4353K_t - 3.4499K_t^2 + 2.1888K_t^3 \]  
\[ 0.175 < K_t < 0.775 \]  
\[ \frac{I_d}{I_g} = 0.26 \quad K_t > 0.775 \]  
\[ I_t = I_b R_b + I_d R_d + I_g R_g \]  
\[ R_b = \cos \theta / \cos \theta_r \]  
\[ R_g = \rho_s (1 - \cos \beta) / 2 \]  
\[ R_d = \left( 1 + \cos \beta \right) / 2 \]

The value of the hourly average terrestrial radiation values \( I_t \) are input for the PV model which explained in the following part.

2.3. PV Model

To predict the performance of a PVPS, a mathematical model of the solar cell is needed. The solar cell can be represented by the equivalent circuit shown in Figure 4. The relationship between current, \( I \), and voltage, \( V \), is [3]:

\[ I = I_L \left[ \frac{V + IR}{R} - 1 \right] \]  
\[ I = I_o \left[ \frac{V + IR}{R} - 1 \right] \]  
\[ I_{ref} = I_{sref} \]  
\[ I_{sref} = \frac{I_{ref}}{e^{A_{ref} c_{sref}}} \]  
\[ R_{sref} = \frac{A_{ref} \ln \left( 1 - \frac{I_{sref}}{I_{ref} - V_{ocref}} \right)}{V_{mref}} \]  
\[ A_{ref} = \mu_{osc} T_{cref} - V_{ocref} + E_a N_s \]  
\[ T_c = T_a + \frac{G}{G_{max}} \left( T_{cmax} - T_a \right) \left( 1 - \frac{T_c}{T_{cref}} \right) \]  
\[ I_l = \left[ \frac{G}{G_{ref}} \left( I_{ref} + \mu_{dc} \left( T_a - T_{cref} \right) \right) \right] \]
\[ I_o = I_{\text{ref}} \left( \frac{T_o}{T_{\text{ref}}} \right)^3 \times e^{-\frac{N_{s} R_s}{A}} \left( 1 - \frac{T_{\text{ref}}}{T_o} \right) \]  
(31)

\[ A = A_{\text{ref}} \frac{T_o}{T_{\text{ref}}} \]  
(33)

\[ R_s = R_{\text{ref}} \]  
(32)

\[ I_L, I_o, R_s, R_{sh}, \text{ and } A \] are five parameters that depend on the incident solar radiation and the cell temperature. Four parameter models, which neglects the shunt resistance \( R_{sh} \) since it is usually very large compared with the series resistance \( R_s \), particularly for single crystalline silicon cells. With this assumption, Eq.(23) can be rewritten as Eq.(24): A method to calculate these four parameters \( (I_L, I_o, R_s, \text{ and } A) \) is summarized as follow. Since there are four unknown parameters, four conditions of \( I \) and \( V \) are needed. However, manufacturers usually provide \( I \) and \( V \) at only three conditions: short circuit, open circuit, maximum power point. The fourth conditions come from the knowledge of \( \mu_{\text{oc}} \) and \( \mu_{\text{sc}} \), the temperature coefficients of open circuit voltage and short circuit current, respectively. Eqs.(25)–(28) are used to calculate these parameters of PV cells at a standard condition based on the experimental data provided by the manufacturer.

The subscripts \( \text{oc, sc, mp, and ref} \) refer to open circuit, short circuit, maximum power and reference conditions, respectively. \( N_s \) is the number of cells in series in one module. Whenever the solar radiation, \( G \), or the ambient temperature, \( T_c \), changes, the cell parameters change and can be estimated from Eq.(29). The cell temperature is obtained from the manufacturer supplied NOCT (Nominal Operating Cell Temperature).

\[ I_{\text{calculated}} \text{ during one year.} \]  

\[ \text{Figure 3. } I_L, I_o, I, \text{ calculated during one year.} \]

\[ \text{Figure 4. Equivalent circuit for a PV generator.} \]
Operating Cell Temperature) conditions. At NOCT conditions of the cell parameters at the operating cell temperature and solar radiation are then found from Eqs.[29:33] The cell model is summarized as follows: Eqs. [25–28] are used to find values of the four parameters at reference conditions. These four parameters are corrected for environmental conditions with Eqs. [29–33], and use in Eq. (25) which relates cell current to cell voltage. A MATLAB model uses equations and the solution steps explained above to obtain the cell characteristics at different solar radiations values. The manufactures data of the PV array module are listed in Appendix 1. The simulation results showed the I-V characteristics of the PV array at different values of solar radiation, started with values from; 140 w/m$^2$ to 1260 w/m$^2$. Figure 5 shows (I-V) characteristics of the PV array at different values of solar radiation, and the power-voltage (P-V) characteristics of the PV array at the same values of solar radiations. Each figure shows the value of solar radiation for each curve. The search algorithm is applied to find the MPP values during various values of radiation. Figure 5; shows the MPP obtained by applying the search algorithm using a MATLAB program for the PV array. In this figure the maximum power point at each radiation values are shown. In Figure 5a I-V curves at different solar radiations values and the voltage and current at MPPT. In Figure 5b the P-V curves at the different solar radiations values and the corresponding MPP at each curve.

![Figure 5. PV performance curves at different solar radiation values and the corresponding MPP at each solar radiations values.](image)

2.4. Simulation Performance of Induction Motor with Scalar Inverter

The simulation model used an induction motor of power 7.5 kw operated with scalar inverter model. The inverter uses a sinusoidal pulse width modulation technique to generate the firing pulses of the power switches. The input DC voltage of PV is changed during the day, so the inverter varies the voltage and frequency in a constant relation to maintain constant motor flux. When the frequency reaches the rated value, the inverter maintains the frequency constant at the rated values and the voltage is increased causing a small change in the pump speed. Figure 6a; shows the motor torque speed c/c when the voltage and frequency are changed in a relation shown in Figure 6b. The voltage frequency is changed in linear relation till the frequency reached the rated value the frequency is maintained constant and the voltage is increased due to the radiation values increases in the PV system.

2.5. Pump Model

The pump model can be simulated as by solving the equations of the head flow curve and system flow rate curve. The manufacturer give data for the pump at rated speed only and by applying the pump affinity laws the relation between pump flow, head and pump torque with the speed can be
determined. The system curve is used by knowing the system static head and the total dynamic head at rated conditions. By using the system curve, and pump characteristics at different speed the operating point can obtained.

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Figure 6. Motor torque speed c/c in case of voltage and frequency change.

Figure 7 explains the pump (Q-H) curves at different speed and also shows the system curve. The intersection between the system curve and Q-H curves give the operating point at each speed. From this operating point the relation between the pump flow, and head with the pump speed is shown in Figure 7b. The torque speed relation can obtaining by calculating the pump power, from the flow rate and the total head at each operating speed, divided by the pump efficiency.

3. Mathematical Algorithm to Calculate the Water Flow Rate Values of the Pump

The simulation algorithm of system shown in Figure 1 is verified as follow; the input for the PV model is the terrestrial radiation ($I_t$), which is generated from the weather model. This input is used by the PV model to calculate the DC voltage. The output voltage of the PV array is input for a MPP model to calculate the voltage corresponding to the MPP. The voltage values results from this model are input for the inverter model. The inverter converts the DC voltage into AC voltage with the suitable frequency. The AC voltage input for the induction motor model. The results of the I. M. model is the torque speed curve at different voltage values. The torque speed curves of the induction motor are used with the torque speed curve of the pump load to calculate the operating speed.

The operating speed is used by the pump model to calculate the pump flow rate, and pump head. The results obtained from this model are; the water flow rate and the total head. These results are used to represent the system performance during one day, one month, or one year depends on the input weather values for the simulation model. The simulations results during one average day for each month are calculated. Figure
8 shows the water flow rate values calculated using simulations models for the solar PV pump systems. The results in this figure is presented in average hourly variation during one day in each month to represents the water flow rate variations during all month days. The results showed that; the largest flow rate values are in summer months such as; June, July, and August during these months the flow rate reached the rated value of the pump (more than 50 L/hr) related to the rated frequency of the motor. And in winter months such as; December, January, and February are the smallest values of water flow rate values. But the other six months during the year the values of water flow rate are nearly take the same variations profile and the same values.

4. Experimental Results

4.1. Experimental System Area

The Ministry of Water Resources and Irrigation proposed two sites; they are located in Kafr Al Dawar- Al Baheira Governorate (Latitude of 30.5° West, and Longitude of 30.3° North) in the Western part of the Nile Delta. The project contains four solar water pumps each one 10 HP rating.

(10.2 KWP each) the system designs to irrigate 230 Fadden. The system contains 48 modules for each one pump. The rated power for the module is 300w. The PV array is installed on the canal after using large pipe for water passing. Figure 9 a, b; show the pumps house, and the PV array used for the system.
4.2. System Flow Rate and Power Measurement During One Day in Different Months

The PV surface pump of rated 10hp is installed in Al-Afeer areas. The performance of the system is evaluated by measuring the pumped water flow rate and the pump power. Ultrasonic flow meters have been used for the flow rate measurements. The power consumption has been measured using three phase power analyzer. All data recorded during the day at each one hour. Figure 10 shows the measurement results during two different days. Figure 10a shows the water flow rate values and the power consumption during 16th July, and Figure 10b; shows the same results during 6th March. The results showed that during 16th July, as the solar radiations values are high and the occurrence of clouds is small so the power values and the water flow rate values are high and maintain constant during the intervals from 9:00am to 3:00pm and the unit give the maximum flow rate values during this period. But in Figure 10b the results obtained in 6th March month, the water flow rate and the power values start with small values and reach the rate values nearly at 11:00am and then maintain constant at rated value for about 3 hours then it decreases at 3:00pm and reach to zero value at 17:00pm. When compare these results with the simulations results shown in Figure 8. It’s seen that; the simulation results take the same profile of the measurement values. So it can be used the simulations models to estimate the system performance during different intervals of time. The total quantity of water during one year can be estimated from the simulation model, which helps the designers to calculate the irrigated areas and the type of crops suitable for the values of water flow rate.

4.3. Electrical Results and Power Quality Analysis

In this the electrical performance of the system during different cases of operation such as in different days, and at different conditions of solar radiations values are analyzed. A power quality analysis device fluke 1760 is used to measure all electrical signals. The accuracy of the device is five reading per second the software of the device calculate the harmonic contents, total harmonic distortion and the instantaneous flicker occurred during system operation. This is in addition to the main electrical signals such as; voltage, frequency, current, power and power factor (P.F.). The analysis were focused on the intervals in which a sudden change occurred in the system operations such as; low radiation values during sun set times, high radiation values during afternoon period, and also during clouds intervals occurred. Two different days; one during summer (16th July), and the other day during winter on (6th March) are using for the discussions.

4.3.1. Electrical Analysis During 6th March

Figure 11 shows the electrical signals recorded by the Power Quality device during day hours, during the pump unit run from sun set to sun rise. Figure 11a; shows the voltage values; its noticed that during sun rise intervals the voltage values start with small value 240V at 8:00am this depends on the solar radiations values during this time of the day. Then the voltage values increase with the time increasing as the solar radiation values increase too till reach 380V at 10:20am, this value is the rated value for the motor. After this time the voltage maintain constant however the solar radiation is increase due to inverter operations. When compare this voltage profile by the frequency profile Figure 11.b we noticed that also the frequency is start with 30hz then increases gradually related to the voltage value to maintain constant flux inside the motor. The frequency values are related to the motor speed which proportional with the pump output flow rate values, and the power consumption by the motor as shown in power values in Figure 11.c. The rated power consumption by the motor during afternoon interval.
less than 9 kw, which depend on the power come from the PV array. the motor P.F. values is shown in Figure 11.d it is seen that the P.F. at small loads during mooring is small its value vary from 0.35: 0.8 and when the motor run at the full load after 10:00am the motor P.F. reach about 0.82 which is the rated value of the motor. Also the harmonic contents varying the value of Motor P.F. as explain later. It’s seen in this figure that during clouds interval from 14:00pm till 15:00pm the system is stop and no feeding water, this occurred periodical during winter months and causes reducing the number of running hours of the unit. It should be take into consideration during the system design the running hours variations due to solar variations which causes variations for the total quantity of waters comes from the PV system.

4.3.2. Electrical Results and Power Quality Analysis in 16th July

In this test all signals are measured during 16th July on the system during the pump run from sun rise to sun set. The results are shown in Figure 12. As explain in the above; for all signals such as; voltage, frequency, power and P.F. The difference in the results are; the voltage values are start with small value and reach the rated value gradually in proportional with the frequency value. The voltage and frequency values are constant at the rated value without change during all the day hours as no clouds occurs during this day. The total power consumptions by the pump is increased during solar noon intervals more than 9 kw, as there is more energy come from the PV array to the motor unit. The motor P.F. is changed from 0.35 till reach the rated values 0.8 and maintained constant at this value during the whole day hours.

4.4. Power Quality Analysis of Surface PV Pump

The power quality of the system during the two different days is studied. The software of the measurement device can calculate the THD%, instantaneous flicker and harmonic contents in the line voltage. Figure 13, 14 shows the results obtained during 6th March day; the THD values in line voltage is very large, there values are varying between 10-15%. The harmonic contents values showed that; the 3rd harmonic contents are very large there values varying in between 10-13%. the 5th, 7th, and 9th harmonic contents values are small less than 0.5%. The 11th, and 13th harmonic values are about 2%. The instantaneous flicker values increase more than 3000 which mean a fast variation in voltage values due to inverter operations this is because of solar radiations changing. Figure 15, 16 show the harmonic contents during 16th July day.
b. Frequency

c. Power
Figure 11. Electrical signals during 6th march.
b. Frequency

c. Power
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d. P. F.

**Figure 12.** Electrical measurements during 16th July.

a. Instantaneous flicker
Figure 13. Power quality signals during 6th March day.
5th harmonics

7th harmonics
c. 9th harmonics

d. 11th harmonics
Figure 14. Power quality signals during 6th March day.

a. Instantaneous flicker

e. 13th harmonics
b. THD %

c. 3rd harmonics
Figure 15. Power quality signals during 6th March day.
b. 9th harmonics

c. 11th harmonic
It’s seen that; the value of THD is reduced to about 7-9%, and the 3rd harmonic values reach about 6%. The 5th, and 7th values are less than 1%, but the 11th, and 13th harmonic contents increases to exceeds 2%. The instantaneous flickers values are around 800-900 which means more stability in the voltage values due to stability of solar radiation values. A comparison between the results obtained in the two cases are shown in Table 2:

|       | THD%  | Flicker | 3rd %  | 5th, 7th % | 9th % | 11th, 13th % |
|-------|-------|---------|--------|------------|-------|--------------|
| 6th March | 10-15 | 3000    | 9-13   | <1         | <1    | <1           |
| 16th July | 7-9   | 850     | 6-8    | <1         | <1    | <2           |

5. Conclusions

In this paper the performance of PV surface pump is introduced. A simulations model for, weather, PV module, motor pump unit are introduced. The simulation results during one year showed that; during summer months the output flow rate of the pump unit are the largest values, and winter month are the smallest value of water flow arte. A good agreement between simulation and experimental measurements for the flow rate values are obtained which means that the simulation model results can be used with acceptable accuracy to represent the pump performance, around the years.

The power quality analysis of the PV pump system during different cases of operations showed that; during low radiation values from sun rise till solar noon the voltage and frequency change in constant proportionality to maintain the flux constant inside the motor and to run the pump at a specified speed related to the energy come from the PV. And during solar noon the inverter make the pump to run at constant frequency which is depend on the mechanical design on the pump, at clouds the system is stopped. Also the starting time of the unit is varying according to the date and time which related to the solar radiation values. The total harmonic distortions values during low solar radiations intervals are high (more than 15%) and the main component of harmonic contents are the 3rd harmonics, also the 11th and 13th harmonics have a large values (more than 2%). The instantaneous flicker values are very high which present more disturbances on the voltage profile. During high solar radiations values and when the pump runs at the rated frequency the values of THD become small less than 9%, and also the flicker value are decreases. From these results it’s recommended that; the motor used with a PV pump should be of high insulation class as it will suffer from high harmonic values. Also the number of PV module should be selected correctly according to the
pump rating power to maintain the unit run at low radiation values giving small amount of water.

**Nomenclature**

\[ \Phi \] latitude angle  
\[ \delta \] declination angle  
\[ \omega \] solar hour angle  
\[ \alpha_e \] solar altitude  
\[ \omega_s \] sunset hour angle,  
\[ \beta \] tilt (slope) angle  
\[ S \] sunshine hours  
\[ I_b \] Beam radiation  
\[ I_g \] Global radiation  
\[ R_b \] tilt factor of the beam radiation  
\[ R_d \] tilt factor of the ground reflected radiation  
\[ I_{sc} \] light current (A);  
\[ I_{o} \] operation current (A);  
\[ R_s \] series resistance (V)  
\[ A \] thermal voltage (V)  
\[ t \] is the cell cover transmittance for solar radiation  
\[ \eta_c \] is the cell efficiency  
\[ L \] longitude angle  
\[ n_d \] day number  
\[ t \] local apparent time  
\[ \gamma_e \] solar azimuth angle  
\[ \theta \] solar incidence angle  
\[ \theta_z \] zenith angle  
\[ I_{0c} \] solar constant = 1367 W/m\(^2\)  
\[ I_{p} \] Diffuse radiation  
\[ I_{r} \] terrestrial radiation  
\[ R_d \] tilt factor of the diffuse radiation.  
\[ \rho_c \] ground reflectivity.  
\[ J_0 \] dark current (A);  
\[ V \] operation voltage (V);  
\[ R_{sh} \] shunt resistance (V)  
\[ E_g \] is the band gap of silicon, (eV) and  
\[ \alpha \] is the cell absorption for the transmitted solar energy.

**Appendix**

PV: \[ P_{mp}=300\text{w}, V_{oc}=45.35 \text{V}, I_{sc}=8.93, V_{mp}=35.87, I_{mp}=8.36, \]
Type: EMMVEE,  
**Motor**: 7.5kw, 380v, 50hz, 0.88pf, 1480rpm, 15A,  
**Pump**: 162M\(^3\)/h=45l/s, 12.7m, 1460rpm.

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