Introduction

Solar power, nowadays, is the most promising type of non-conventional source of energy. In Egypt solar energy is used on a small scale in some applications; although it has high values of solar radiations (Bagher, Vahid, & Mohsen, 2015) and sunshine hours (Sumathi, Kumar, & Surekha, 2015). Solar energy can be used in different schemes such as: thermal applications and photovoltaic applications (PV) (Ranabhat et al., 2016). PV has many types of manufacturers and applications. After the first trial for assessing a pilot rooftop 90 kW PV system in Qanater, Egypt (AbdelHady, 2017), more accurate information on system configuration became available as well as more reliable recorded output series (MERI, 2016). In this paper the actual manufacturer, ones replace the assumed inverters characteristics in the first trial. Records of the newly installed energy meter are used as a base for system’s performance assessment. AbdelHady’s (2017) recommendation of tying the system to national grid was taken into consideration. Therefore, in this paper tying to the national grid is the only simulated scenario.

Types of photovoltaic cells

There are many types of solar modules and technologies. The most common are the silicon PV technologies. Figure 1 shows four different types of silicon PV cells. The difference between these types is the percentage clearness of silicon atoms. The best distribution of silicon molecules increases the cell convergence of sunlight to electrical energy (Chander, Krishna, & Srikanth, 2015). There are four common types of silicon PV cell in the market (monocrystalline solar panels (Franklin, 2017), polycrystalline solar panels (Mather & Wilson, 2017), thin film solar panels and hybrid silicon solar panels (Parida, Iniyi, & Goic, 2011)). The main specifications of polycrystalline solar panels are described in below as it’s the type used in our system.

Polycrystalline solar panels

This type of solar cell is more economical than monocrystalline type. Its efficiency is 13%, so it is less than the above type. But due to its relatively small cost, it is widely used in home applications (Mather & Wilson, 2017). The main disadvantage of polycrystalline, is that it needs large system installation area. The module in our system is of this type (Suntech Power STP255-20-Wd).

Solar power systems applications

Solar power systems can be used in different applications such as: stand-alone systems (off-grid), or on-grid systems. The main types of solar systems used in domestic applications are on-grid, off-grid and on-grid with batteries storage (Farhoodnea, Mohamed,
Shareef, & Zayandehroodi, 2013), (El-Shimy, 2009), (Ayompe, Duffy, McCormack, & Conlon, 2011). The difference between those types of systems are how they are connected to the electricity grid network. Each type has its advantages and disadvantages.

**On-grid PV systems**

In this system the electrical output power coming from the solar system is directly connected to grid, and also connected to the house. The loads in the house use the electric energy from the PV system and also the electric energy of the grid. Depending on the solar radiations and the electric energy generated by the PV system, the load can take all of the required energy either from the PV system or can be shared between the PV and the electric grid. In case of light loads and high generated energy of PV system, it can be fed into grid through an electric meter. According to the recommendation from (AbdelHady, 2017), an electric meter was connected to the system in July 2016 so the excess generated energy is not dissipated.

**Types of solar inverters**

Inverters are used in different types of solar systems to match the generated energy of the PV panels with the electrical grid (Yilmaz & Ozcalik, 2015). Inverters use different technologies to convert DC energy, produced from PV cells, into AC (De Lima, De Araujo Ferreira, & De Lima Morais, 2017), (Kymakis, Kalykakis, & Papazoglou, 2009). Costs of inverters vary according to the wave shape of the output AC sine wave. The more the inverter produces a pure sine wave, the higher its cost. Inverters control the system’s energy, monitor and record all data of the system, plus produce faults due to any mal functions. The main types of inverters used in PV systems are (string inverters (Khan, Asif, & Stach, 2017) used in our system, central and micro inverters (Swoop, 2014)).

**String inverters**

Any PV system contains different number of PV panels and the connection depends on the required voltage and current. The solar panels are connected together in the PV system in a string, which contains a specified number of PV panels. Each string output energy is connected to an inverter. The output of these string inverters are connected together and then the output is connected to grid or to loads. In case of shadow occurring on a PV string, only this string doesn’t feed energy into grid while the other panels operate (Khan et al., 2017). The system uses four inverters (20 kW rated power) and one (10 kW rated power) as shown in Figure 2b. Each inverter of 20 kW power is connecting to 80 PV modules connected as 20 models in series and four strings in parallel.

Figure 3 shows the connection of all systems modules and inverters to grid. The system installation area is about 600 m² on the roof of a building as shown in figure 2a. It consists of 360 modules, the rated power of each module is 250 W.

The output voltage and frequency of inverters are 380 V, 50 Hz. All inverters’ output is connected to the local grid using a circuit breaker. The operation of the on-grid inverter is to maintain the voltage and frequency of the AC output voltage within permissible limits to be compatible with grid voltage and frequency at different solar radiation values. The on-grid inverter measures the grid voltage and frequency to synchronize with it. In case of power failure or any changed grid voltage or frequency beyond the permissible limits the system doesn’t feed any energy regardless how high the solar radiation is. The generated energy from the solar PV panels is varied during the day hours, as it starts with small value during sun rise and increases gradually till it reaches maximum at noon, after that it decreases again to reach minimum at sunset. Also the generated energy changes from 1 month to another, the maximum is achieved in summer.

**Assessment of PV system performance**

**Solar radiations and temperature values at the installation area**

To study the performance of any PV system, the solar radiation and temperature values in the location of the
system installation should be determined. The average solar energy values for our system location (longitude 31.3, latitude 30.1) is calculated and measured by Ret-screen program (NASA, 2018). The average monthly temperature over 5 years is estimated from (World weather online). The solar radiations (kW/m²/d) and temperature (°C) values are given during different months of the year as shown in Table 1. The maximum values reached are 0.75 and 0.73 kW/m² in June and July, while the lowest solar radiation values attained are in December and January (0.28 and 0.3 kW/m²). These values are used to calculate the solar cell system performance, and estimate the power generated by each cell by applying a simulation model as explained in the following part.

**PV cell mathematical model**

A simulation model of solar cell is formulated to predict and calculate the potential output power of the PV cell (Shah & Biate, 2016), (Ayaz, Nakir, & Tanrioven, 2014), (Huld & Amillo, 2015). The PV cell can be simulated by the circuit shown in figure 4.

The correlation between cell current, $I$, and cell voltage, $V$, is shown in equation (1):

$$I = I_{ph} - I_o \left( e^{\frac{V + I R_s}{a}} - 1 \right) - \frac{V + I R_s}{R_{sh}}$$

(1)

where $I_{ph}$ is the photocurrent, $I_o$ is the saturation current of the diode, $R_s$ is the series resistance, $R_{sh}$ is the shunt resistance, $a$ is the thermal voltage. $I_{ph}$, $I_o$, $R_s$, $R_{sh}$ and $a$ are five parameters that depend on the solar radiation values, and the surface temperature of the cell. By neglecting $R_{sh}$ since it is usually very large compared to $R_s$, equation (1) becomes as follows:

$$I = I_{ph} - I_o \left( e^{\frac{V + I R_s}{a}} - 1 \right)$$

(2)

To calculate the four factors ($I_{ph}$, $I_o$, $R_s$, and $a$) the following steps are applied:

In equation (2) there are four unknown factors, so four constrains are needed. For any cell the values for $I$ and $V$ at three conditions: short circuit current $I_{sc}$, open circuit voltage $V_{oc}$, maximum power point (MPP) ($I_{MPP}$, $V_{MPP}$) are known. These conditions come from knowing of $\mu_{Voc}$ and $\mu_{Isc}$, the temperature factors of open circuit voltage and short circuit current ($\mu_{Voc}$, $\mu_{Isc}$). So equation (3) to equation (6) are used to calculate these factors of PV cells at reference conditions (NOC) based on the experimental data provided by the supplier.

$$I_{ph_{NOC}} = I_{sc_{NOC}}$$

(3)

$$I_{oc_{NOC}} = \frac{I_{ph_{NOC}}}{ \left( \frac{V_{oc_{NOC}}}{e^{I_{ph_{NOC}}}} - 1 \right)}$$

(4)

$$R_{NOC} = \frac{a_{NOC} \ln \left( 1 - \frac{I_{MPP_{NOC}}}{I_{sc_{NOC}}} \right) - V_{MPP_{NOC}} + V_{sc_{NOC}}}{I_{MPP_{NOC}}}$$

(5)

$$a_{NOC} = \frac{\mu_{Voc} \mu_{Isc} T_{NOC} - V_{oc_{NOC}} + E_g N_s}{\left( \frac{\mu_{Voc} T_{NOC}}{\mu_{Isc} T_{NOC}} \right) - 3}$$

(6)

where the subscripts $oc$, $sc$, $Mpp$ and $NOC$ refer to open circuit, short circuit, maximum power point and normal operating conditions respectively. $T_{NOC}$ is the nominal operating cell temperature specified by the manufacturer, $E_g$ is the band gap of silicon and $N_s$ is the number of series cells in one module. Whenever
the solar radiation \((G)\) or cell temperature \((T_c)\) change, the cell parameters change according to equation (7).

\[
T_c = T_a + \frac{G_{NOC}}{G} (T_{NOC} - T_a) \left( 1 - \frac{\eta_c}{\tau} \right) \quad (7)
\]
where $\tau$ is the cell cover transmittance for solar radiation, $\alpha$ is the cell absorption for the transmitted solar radiation and $\eta_c$ is the cell efficiency at normal operating conditions. The cell parameters at the operating cell temperature and solar insulation are then deduced from equation (8), equation (9), equation (10) and equation (11):

$$I_{ph} = \left( \frac{G}{G_{NOC}} \right) \left( I_{phoc} + \alpha \eta_c (T_c - T_{NOC}) \right)$$  \hspace{1cm} (8)

$$I_o = I_{phoc} \left( \frac{T_c}{T_{NOC}} \right)^3 e^{\left( \frac{\eta_c}{\alpha} \right) \left( 1 - \frac{T_{NOC}}{T_c} \right)}$$  \hspace{1cm} (9)

$$R_s = R_{NOC}$$  \hspace{1cm} (10)

$$a = a_{NOC} \frac{T_c}{T_{NOC}}$$  \hspace{1cm} (11)

The mathematical model calculates the cell parameters by applying equation (3) – equation (6) to find values of the four factors at normal operating conditions. These four factors are corrected for environmental requirements by applying equation (8) – equation (11). The cell current to cell voltage is calculated by using equation (2). Matlab Simulink model (AbdelHady, 2017) with modification use the above equations and follow the solution steps to calculate the cell parameters at different solar radiations values (Yatimi & Aroudam, 2016). The solar cell used in this model as specified earlier is of type (Suntech 250 W). The manufactures data of this cell are listed in Appendix 1. The IV curves of the PV cell at various values of solar radiation starting from 100 W/m² to 1000 W/m² covering all ranges of radiation values during the year. Figure 5 shows IV/PV characteristics of the PV array at different values of solar radiations and temperatures. The MPP of the cell at different solar radiations values is calculated by applying search algorithm. The corresponding voltage and current values at MPP is calculated and marked on each curve.

**Model validation**

The model is first tested under standard temperature conditions (STC): radiation 1000 W/m² and temperature 25°C for validation and testing of the new components added and compared with the maximum power of the array computed from equation (12) (90 kW), where $V_{MPP}$ and $I_{MPP}$ are 30.8 V, 8.28 A respectively

$$P_{max.} = V_{MPP} \times No. \ of \ series \ modules \times I_{MPP} \times No. \ of \ parallel \ strings$$  \hspace{1cm} (12)
Table 2. Monthly averaged sunlight hours in Qanatir.

| Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sept | Oct | Nov | Dec |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|------|-----|-----|-----|
| Sunlight hours (hrs) | 10:26 | 11:04 | 12:00 | 12:54 | 13:40 | 14:03 | 13:52 | 13:12 | 12:20 | 11:25 | 10:38 | 10:14 |

![Figure 6](image_url)

**Figure 6.** Monthly generated energy during the year 2016.

**Monthly energy estimation of the system**

By implementing the system module connections of all panels (80 modules for each 20 kW inverters, and 40 panels for 10 kW inverter), using the system configuration (7 panels in series and 51 strings in parallel) and applying the mathematical models of the solar module; the overall system voltage, current and power according to different values of solar radiations and temperature are calculated. Using the actual values of average monthly solar radiation and temperature (Table 1) (NASA, 2019) the monthly power generated from the model is calculated multiplied by the average daylight hours (Table 2) (NASA, 2019) to determine the energy generated (equation 13) and compared with values recorded by the inverter software (MERI, 2016).

\[ E_{\text{monthly}} = P_{\text{monthly}} \times \text{Daylight hours}_{\text{monthly}} \times \text{month days} \times 10^{-3} \] (13)

**Annual generated power of the system**

The yearly generated energy during the years 2016 to May 2020 is calculated by the model and compared with the inverters reading. The monthly radiation and temperature are entered to the Simulink model; each month is calculated according to equation (13) and added for each year.

**Results**

**Model validation**

By testing the model under standard temperature conditions (STC) for validation and testing of the new components added and comparing with the maximum power of the array computed from equation (12) (90 kW), where \( V_{MPP} \) and \( I_{MPP} \) are 30.8 V, 8.28A, respectively. The median of the simulated results is deduced so that the outliers don’t affect the results, the \( P_{\text{maxTracked}} \) is 79 kW making the overall efficiency of the maximum power point tracking (MPPT) technique (AbdelHady, 2017) 87.8%.

**Monthly energy estimation of the system**

Figure 6 shows the monthly generated energy during the year 2016. The energy from the Simulink model is calculated using the actual illumination (NASA, 2018), sunlight hours (NASA, 2019) and temperature (World weather online, 2020) (Potential Energy Calculated). These values are compared with the energy recorded by the inverter software (Energy Measured).

It is noticed that the maximum energy generated from the system is during the months of June and July due to high solar radiances values (0.751, 0.731 kW/m²) while the minimum values are in December, January and February. The measured results showed that the energy achieved in July (12.6 MWhr/month). While during May, June, and August is about 11.5 MWhr/month regardless that June has a higher...
radiation value than July due to other conditions affecting the on-grid system performance. The calculated values follow the PV characteristic curve which increase with radiation. The deviation between the actual energy calculated and the average energy calculated is not significant. The highest actual energy calculated is achieved in June and July (23.4, 23.2 MWhr).

The minimum recorded generated energy occurs in January (5.3 MWhr). The generated energy in October, November and December are also low due to low solar radiation (Table 1) and also the limited sunlight hours in these months (Table 2). The minimum calculated energy occurs in December (6.1 MWhr).

By comparing the results obtained by the mathematical model shown in figure 6, it is noticed that there is a deviation between the calculated and measured values during all months. The standard deviation (σ) between the measured results and the Simulink model is 8.783 MWhr. The reasons of those deviations are the conditions affecting the operation of the system such as: power failure, cleaning of the panel surface, and also the weather parameters variation such as: wind, fog and clouds.

Annual energy estimation of the system
Accumulation of the generated energy during each months is done to calculate the annual generated energy (110 MWhr/year). When this value is compared by the average results from the model (176 MWhr), it is noticed that the system actual annual generated energy is 62.5% of the design value due to conditions explained previously affecting the system operation.

Conclusions
This paper assesses the electrical performance of 90 kW On-Grid PV system installed in Qanatir, Egypt. A Matlab Simulink program is modified to calculate the PV module generated power at different solar radiation and temperature values. The output energy of 90 kW PV On Grid system is measured continuously on hourly basis. The monthly generated energy is calculated and the maximum generated energy is obtained during June and July about 12 MWhr, and the minimum values are obtained in January and December (5 MWhr). By comparing the actual power generated by the system with those obtained from the mathematical model, a deviation is noted during all months. The reasons of this deviation is due to the different conditions that disturb the operation of the system such as power failure, cleaning of the panel surface, and also the weather variation parameters. The system actual generated energy per year is 62.5% of the design value. This indicates that the system needs periodic cleaning of panel surface and reduction of power failure intervals, to benefit from maximum amount of generated energy.

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Appendix 1; values of PV module constant

| Parameter | Value       |
|-----------|-------------|
| $I_{sc}$  | 8.76        |
| $I_{mp}$  | 6.68        |
| $V_{oc}$  | 37.6        |
| $V_{mp}$  | 28.1        |
| $\mu_{voc}$ | -0.33    |
| $\mu_{isc}$ | +0.067    |
| $T_{c}$   | 293         |
| $T_{ref}$ | 293         |
| $G_{ref}$ | 1000        |
| $e$       | 1.155       |
| $n_s$     | 60          |
| $c_{ij}$  | 0.9         |
| $c_{ec}$  | 0.075       |
| $T_{noct}$ | 339       |
| $a_T$     | 0.2         |
| $\eta_c$  | 15.4%       |