Performance Evaluation of PV Plant at Al-Ahliyya Amman University in Jordan

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Abstract. The objective of the paper is to analyse the technical performance over 2018 of the grid-tied 1MWp solar PV plant installed on the roofs of eight buildings at the campus of Al-Ahliyya Amman University (AAU) in Jordan. The plant comprises 3869 modules of 260 Wp each, oriented due south with mixed tilt angles of 5° and 10°. The structure of the plant is configured as eight PV units connected in parallel to the main distribution substation 11 kV/0.4 kV. The plant SCADA system is designed using Internet of Things and programmable logic controllers. According to the conditions of the electricity utility, the SCADA system controls the output of inverters to prevent any injection of PV power in the grid. This utility restriction is found to lead to bad evaluation indicators. According to the evaluation results, the measured specific yield (1203 kWh/kWp) is less than the estimated one without restriction (1727 kWh/kWp) by about 30%. Whereas the annual yield as computed by software PVSYST V5.71 amounts 1737362 kWh, the measured yield considering the utility limitations is 1203380 kWh. Accordingly, the capacity factor (13.7%) and the performance ratio (62.5%) are found to be significantly reduced.

1. Introduction

Al-Ahliyya Amman University (AAU) is a private university in Jordan since 1990. AAU consists of 15 buildings used for the seven faculties, a work shop, accommodation facilities, cultural complex (Arena), and a house for car parking. The buildings covers around an area of 73000 m². The university consumes about 3.3 GWh electricity per year.

As the solar insolation at site is very high (over 5 kWh/m²/day), and to lower the electricity bill which is based on about 36 $cents/kWh, AAU installed two grid-connected PV plants. The fist plant was installed in 2014 on Arena roof with a capacity of 276 kWp [1], and the second plant was installed in 2017 on the roofs of eight buildings with a total capacity of 1 MWp (Figure 1.).

Figure 1. PV subsystem of a building at AAU
The installation of the energy part of the 1 MWp system started in 2017 and continued a few months. After that, the SCADA system has been built and the whole system was examined by National Electricity Authority who gave the permit for grid connection. In this paper, the data available by SCADA are collected and then analyzed with a view to making a quantitative assessment of the performance of the solar station over the year 2018 and reaching conclusions about its feasibility, taking into account the restrictions imposed by the electricity company on the production of the plant so that the grid cannot be provided with any capacity.

2. General description of PV plant
The plant uses 3869 modules of 260 Wp each, with mixed tilt angles of 5° and 10°. The PV plant has a total of 36 solar inverters ABB and is configured in a way that the system has 8 PV subsystems, which are connected to transformer 1 (4 subsystems) & transformer 2 (other 4 subsystems) located in the main distribution substation 11 kV/0.4 kV. The plant is equipped with a SCADA system which is connected to the internet and gives the data on an hourly basis. According to the conditions of the electricity company, the SCADA system controls the output of inverters to prevent any injection of PV power in the grid. The PV plant has been installed in 2017, and most of the buildings subsystems has started operation in April 2017, and the last one in August 2017. The datasheet of the module of type BYD P6C-30 Series used in the plant is included in Table 1.

### Table 1. Data of the used module at STC [2]

| Item                      | Values                                      |
|---------------------------|---------------------------------------------|
| Model Type                | BYD 260P6C-30                               |
| Cells per module          | 60                                          |
| Cell Type and dimension   | Polycrystalline Silicon 156*156 mm          |
| Pmax                      | 260 Wp                                      |
| Module efficiency         | 15.98%                                      |
| Power Tolerance           | 0-5 W                                       |
| Vmp                       | 30.67 V                                     |
| Imp                       | 8.48 A                                      |
| Voc                       | 38.38 V                                     |
| Isc                       | 8.97 A                                      |
| Maximum System Voltage    | 1000 VDC                                    |
| NOCT                      | 45°C ±2°C                                   |
| Voltage coefficient       | -0.32 %/°C                                  |
| Current coefficient       | 0.059 %/°C                                  |
| Power coefficient         | -0.34 %/°C                                  |

The system uses 36 solar inverters, 31 of which are of type TRIO-27.6-TL-OUTD-S2X (ABB), and the rest is of type TRIO-20.0-TL-OUTD-S2X (See Table 2.).

3. SCADA System [4], [5]
The control system was designed and built mainly to achieve the following condition imposed by the utility: “PV system generated power shouldn't exceed the imported power of the sum of two transformers”. This means that the control system should control power generated by all inverters and preventing reverse power at both transformers.

### 3.1 System hardware
Each building contains mainly the following components:
A- AC panel: AC panel is a panel built with main motorized circuit breaker controlled by DSEP100 G59 protection relay and the output is connected directly to MDB panel (grid) in that building. G59 protection relay is responsible of connecting and disconnecting PV system to/from grid depending on protection settings of voltage and frequency entered by electrical company.
B- DSE857 (USB TO RS485 communication device): It converts DSEP100 controller USB port to an RS485 port and allows remote connections of up to 1.2 km to monitor a DSEP100 Controller status and integration of DSEP100 controller into an external SCADA or PLC.

C- Link150 (RS485 TO ETHERNET communication device): It converts serial devices connected over RS485 port to Ethernet TCP Modbus and allows remote connections of serial devices over Ethernet and integration into an external SCADA or PLC. Serial devices connected to Link150 are:
- PV inverters.
- DSE857 (USB TO RS485 communication device).
- InteliPro (protection and power relay unit).

Each Link150 is defined over LAN network by unique IP address.

| Table 2. Specifications of used solar inverters [3] |
|-----------------------------------------------|
|                | TRIO-20.0-TL | TRIO-27.6-TL |
| Max. efficiency | 98.2%        | 98.2%        |
| European efficiency | 98.0%    | 98.0%        |
| Rated DC input power | 20.75 kW   | 28.6 kW      |
| Max. DC input voltage | 1000 V     | 1000 V       |
| Number of independent MPPT | 2          | 2            |
| Maximum DC input current | 50 A       | 64 A         |
| Max. input current per MPPT | 25 A       | 32 A         |
| Operating DC input voltage range | 301-950 V  | 301-950 V    |
| DC input voltage range with parallel configuration of MPPT at Pacr | 440-800 V  | 500-800 V |
| Rated DC input voltage | 620 V       | 620 V        |
| Rated AC power | 20 kW        | 27.6 kW      |
| Maximum apparent power | 22.2 kVA    | 30.0 kVA     |
| AC voltage range | 320-480 V    | 320-480 V    |
| Maximum AC output current | 33 A        | 45 A         |
| Rated output frequency | 50 Hz / 60 Hz | 50 Hz / 60 Hz |
| Harmonic Distortion of Current | each <3%, total<5% | each <3%, total<5% |

D- InteliPro (protection and power relay unit): At each transformer MDB there is an InteliPro device. Its main function is to provide plant power readings. Power readings are used by PLC controller to calculate inverters generation set point.

E- PLC (Programmable Logic Controller): There are two PLCs used to control PV plant system:
  - E.1- PLC1: Schneider TM221C24T in transformer 1 electrical room. The function of this PLC is to transfer feeding source position to main PLC. The PLC transfers a signal of ATS panel that indicates presence of main grid utility. If the backup generator starts running, then PV system connected to transformer 1 is ordered to turn off immediately.
  - E.2- PLC2: this is the main PLC that processes all control over plant. PLC used is Modicon M340 and consists of the following parts:
A- Rack: BMX XBP 0400 rack (4 slots). The rack is the part where all PLC components are installed and connected to each other.

B- CPU (Central Processing Unit): BMX P34 2020.

The CPU is the main part of the PLC system and it contains the program application software responsible of managing the required operation sequence and implementing all related commands and conditions. CPU controls inverters over LAN through Link150 devices and it directly sends power production setpoint order. In addition, CPU calculates the power imported from each transformer in order to be able to determine set points. If the backup generator at AAU starts operation in case of any transformer outage, the CPU puts connected inverters to that transformer into off operation mode immediately.
C- Communication module BMX NOR 0200: It is DNP3 protocol communication module, to establish access to system control as required by electrical company.

D- Digital input module BMX DDI 1602:

3.2 SCADA system software
The software used to build SCADA system is called “Struxure Ware SCADA Expert Vijeo Citect 2015” or in short name “Vijeo Citect 2015” V 7.5 SP1. SCADA system links all field devices and perform any required data read/write from/to devices in graphical built pages that represent any plant layout. There are five runtime pages as follows:
1) Startup page (Figure 2): It is the first page displayed when starting runtime. This page always contains the summary of the plant.

![Figure 2. Startup page](image)

2) General zones page: In general zones page the operator/system observer can see all building plants and inverters distributed over these buildings. In each building view, the inverters installed are displayed with main electrical parameters, links to detailed inverter page and links to SLD (Single Line Diagram) page.

3) Plant trend and control page: The operator/system observer can display plant main parameters in trend view and retrieve old trending data which simplify system analyzing. In addition this page contains the main control selection mode. There are two modes to operate the PV control system: Auto mode and Manual mode. In auto mode the main RTU controls all plant inverters production set point and turning ON and OFF depending on previously mentioned operation sequence without need to human interact.

4) Inverter parameters page: In this page all inverter electrical parameters and operation conditions are displayed.

5) SLD (Single Line Diagram) page: In this page a SLD diagram shows the electrical connection in single line diagram view of installed inverters and coupling to grid. Pressing inverter icon displays inverter related control pop up window to control individual inverters ON/OFF and set point. This window will take place only if the system mode is turned into manual mode. In auto mode any command here will be override by RTU program and will has no effect.

4. Performance ratio (Conversion efficiency)
The performance ratio is expressed in % and refers to the relation between the actual AC yield and array DC yield of plant, telling about the PV plant quality. It is also called “conversion efficiency” giving the actual net energy used to be injected into the grid with thermal and conduction losses subtracted. The higher the performance ratio, the PV station operates more efficiently. A performance ratio of around 80% is typical for recent solar PV plants at the first year of operation, and over time, PR
will degrade [9]. The performance ratio is usually calculated for a month or a year as the measured inverter output energy divided by the PV array DC energy at STC [6], [7], [8], [9]. The annual PR% is calculated as

$$\text{PR/year} = \frac{\text{Measured Yield}}{\text{insolation} \times \text{array area} [m^2] \times 365 \times \eta_{\text{module}}}$$

(1)

Whereas the annual yield as computed by software PVSYST V5.71 amounts 1737362 kWh, the measured yield considering the utility limitations is 1203380 kWh. As the utility kWh cost is $0.36, the monetary loss per year is therefore estimated to about $(1737362 - 1203380) \times 0.36 = $192233.52.

The active array area required in equation (1) is calculated as “cell area x number of cells in a module x number of modules”. The solar insolation of the site is taken from the database of software PVSYST, which is originated to NASA-SSE Satellite. As the available insolation is on a horizontal surface, the global monthly average insolation should be computed on the tilted collector by using the program PVSYST. Figure 3 shows the monthly insolation. It is found that a value of 5.848 kWh/m²/day for the average global insolation on the tilted collector plane over a year.

![Figure 3. Global monthly average insolation at AAU](image)

The measured energy production of the PV plant for months 1 to 12 in 2018 is shown in Figure 4.

![Figure 4. Measured energy production for January-December 2018](image)

The PR value of about 63% for AAU plant is a low value; the reason is that, according to the conditions of the electricity company, the SCADA system controls the output of inverters to prevent the injection of PV power in the grid. The PV plant is simulated by the program PVsyst. The simulation results show that the estimated annual energy produced is found to be 1737362 kWh/year with a specific final yield of 1727 kWh/kWp/year, and the system performance ratio is found to be 89.67%. That means, the utility limitations will decrease the generated energy by about 27% at least. The PR value of the PV system without restrictions shows that the system losses are about 11%, where the actual PR refers wrongly to losses about 38%. The causes of the losses are DC and AC wiring, module soiling, power conditioner efficiencies, modules mismatch, deviation from STC, etc.
5. Capacity factor (CF)

The capacity factor (CF) is an important indicator for quantifying the behavior of any power plant. Its definition is the percentage of actual annual production of electric energy to the energy that is supposed to be generated if the plant were permanently operating at full nominal capacity. The capacity varies mainly depending on the type of fuel used in the power plant. The power factor is therefore used as a criterion for comparing the behavior of generating plants using different fuels [10], [11]. It is worth noting that environmental data is not taken into account for the capacity factor while the opposite is true for performance ratio.

The annual CF for a solar PV generation can be calculated using equation (3) adopted by NREL [1]:

\[
\text{CF}/\text{year} = \frac{\text{Actual yield kWh}}{\text{DC Rated power} \times 8760} \times 100
\]  

(3)

The annual CF for our PV plant with consideration of utility limitations is

\[
\text{Annual CF} \% \text{ (AAU PV plant)} = \frac{1203380 \text{ kWh}}{1005 \text{ kW} \times 8760} \times 100 = 13.7\%
\]  

(4)

Whereas CF% without consideration of utility limitations is

\[
\text{Annual CF} \% \text{ (AAU PV plant)} = \frac{1737362 \text{ kWh}}{1005 \text{ kW} \times 8760} \times 100 = 19.8\%
\]  

(5)

Again, due to utility conditions particularly that no PV power injection into grid is allowed, the capacity factor has a lower value than CF without utility limitations.

As of reports on capacity factors of PV generation farms in different countries/cities included in [12], [13], and [14], annual CFs of solar plants in Massachusetts-USA, Arizona-USA, UK, and Egypt, are 13-15%, 19%, 8.6%, and 18.12% respectively. Compared to the solar plants in the above countries, our capacity factor is very high regardless of the utility’s limitations.

6. Conclusions

The analysis of the performance of the AAU 1 MWp grid-tied solar PV power station over the year 2018 has been performed using basic indices such as specific energy production (SEP) [kWh/kWp], capacity factor (CF%) and performance ratio (PR%). According to limitations imposed by the utility, the SCADA system controls the output of plant inverters to prevent the injection of PV power in the grid. The analysis of measured data and its comparison with simulation results obtained by the software PVSYST V5.71, indicated that the limitations have resulted in bad evaluation parameters. Comparing the actual annual parameters SEP, CF%, and PR% (1203 kWh/kWp, 13.7%, and 62.5%) with the “free” parameters (1727 kWh/kWp/year, 19.8%, 89. 67%), shows that the reduction in each of these parameters is about 30%. Whereas the annual yield as computed by software PVSYST V5.71 amounts 1737362 kWh, the measured yield considering the utility limitations is 1203380 kWh. As the utility kWh cost is $0.36, the monetary loss per year is therefore estimated to about $192233.52.

In short, it can be concluded that the overall performance of the studied PV plant is excellent if the company’s restrictions are not present. However, the Performance with existing limitations is somewhat satisfactory. To overcome the utility limitations, a proper storage system should be established. However, the decision can be taken after performing a feasibility study of the issue.

7. References

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