Efficiency Assessment of an Inverter based on Solar PV Energy in Baghdad City

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ABSTRACT

The yearly energy yield of a Solar Photovoltaic (SPV) system is a rendition pointer utilized by the erector to determine the output energy generated by it. From the energy speculation, the payback period and the return on investment can be contemplated. The system energy yield formula consists of many parameters, the most important of which is the SPV inverter efficiency. The European and peak (maximum) efficiency factors from the inverter data sheet are typically utilized, but this utilization is unsound because the SPV does not always work at the peak of its effectiveness due to varying irradiance. The inverter's weighted efficiency is considered more sound as it deems the inverter output power peculiarities. The European weighted efficiency is the most widely accepted inverter efficiency determination. Since it is derived and documented on a rimmed European irradiance profile, it may not be appropriate for inverters constructed in different climatic conditions, especially in the equatorial and subtropical environmental regions. This work aims to formulate a fangled weighted efficiency equation for the inverter's work in the Iraqi environment (especially in Baghdad city as a case study) documented on the IEC 61683: 1999 Standard and Irradiance-Duration curve. The sophisticated formula is endorsed on experimental data from the field using an SMA-SB-4000-TL inverter. It was found that the speculated energy yield using the derived efficiency formula for the Baghdad environment closely matches the energy yield of an original 4.0 KW SPV inverter system with only 1% difference between the determined and acquired values. This means that the employment of the Baghdad weighted efficiency in place of the European or peak weighted efficiency will result in a sounder speculation of the system energy yield, return on investment, and payback duration of the SPV system project.

Keywords-solar PV system; PV inverter; weighted efficiency; energy yield; irradiance duration curve

I. INTRODUCTION

Before the implementation of an SPV system, the designer must estimate the suitability of the site position and deliver the energy yield (E_{sys}) report to the client. The report allows for payback duration and Return on Investment (RoI) speculation. The most important parameter in E_{sys} calculation is the SPV inverter efficiency. Many designers of SPV systems utilize the peak efficiency of the inverter from the data sheet to compute the energy yield from the system. The maximum efficiency (η_{max}) of the inverter is accomplishable under the Standard Test Conditions (STC), which are determined at 1000 W/m^2 irradiance and 25 ^{o}C, although the actual SPV system may rarely function at STC [1-2]. The inverter weighted efficiency estimates, such as the European (η_{EURO}) and California Energy Commission (η_{CEC}), can be utilized instead of the syatem's energy yield determination. The weighted efficiency determination is documented on the fact that the inverter does not always work at STC and is exposed to variations in irradiation and temperature. The efficiency of the inverter is affected by its own losses (due to the control circuits) and by losses deriving from the load variation. The weighted efficiency is considered more reliable for the inverter's efficiency estimations [3]. The weighted efficiency refers to a certain climatic area and its utilization in varying weather conditions, which can produce unsound energy yield (E_{sys}) estimation. For example, an inverter function in Europe will not provide the same power output if it is constructed in Equatorial or Subtropical areas because of the two areas' difference in the irradiance profile and temperature. Up to date, most SPV system designers still deem η_{EURO} and η_{max} as the benchmark for efficiency determination. With the recent rapid growth of SPV systems in subtropical regions, such as Iraq, there is a need for a more solid energy yield speculation from the SPV systems.

The current work has two aims: to prove the assumption that if the SPV system is constructed in a subtropical area like Iraq, the employed η_{max} and η_{EURO} from the data sheet will not be sound and to establish a formula for inverter weighted efficiency for the Baghdad area based on the IEC 61683: 1999 Standard. To fulfill these targets, acquiring a one-year in-plane irradiance dataset from a weather station is crucial. The irradiance data are used as the input to the solar PV array system, which then feeds the inverter under test. The output of the inverter is linked to the AC grid, whereas the input DC power to the inverter and the output power from the inverter are categorized to rimmed actuation classes. From these data, the weighted efficiency of the inverter type SMA-4000-SB-TL is determined and compared with the values given in the datasheet of the inverter. To assert the correct Baghdad weighted efficiency (η_{BAG}), the derived formula is applied to calculate the E_{sys} and the result is compared with that calculated by η_{EURO} and η_{max}. These calculations are then compared with the feasible measurement taken from a 4.0 Kw inverter solar PV system.

II. SOLAR PV INVERTER WEIGHTED EFFICIENCY

The solar PV inverter is the most important part of the SPV system due to the long living cycle of the system, i.e. over 25 years. Also, the inverter efficiency has affected the gross system performance. The energy yield of the system in kWh can be calculated as [1, 2]:

$$E_{sys} = P_{panels} \,.\, PSH.\, f_{mm} \cdot f_{temp} \cdot f_{dirt} \cdot \eta_{cable} \cdot \eta_{inv} \quad (1)$$

P_{panels} indicates the rated power of the system modules, PSH represents the maximum hours of irradiance during the designated month or year, f_{mm} is the mismatch factor of the manufacturer, f_{temp} is the wastage due to temperature, f_{dirt} is the wastage due to the accretion of dirt on the panel surface, and η_{cable} is the efficiency of the DC cable link between the panels and the inverter input side. The last term (η_{inv}) is the inverter efficiency. An inverter that is 1% less efficient is deduced to be 10% cheaper [4]. The inverter efficiency is the ratio of the output A.C. power to the input DC power. A Maximum Power Point Tracker (MPPT) is used to track the maximum point of the module's P-V characteristic curve of the system modules as input power to the inverter at any given temperature and irradiance level. In a simplified determination of E_{sys}, the designers assume η_{inv} is equal to η_{max} or η_{EURO}.

Maximum efficiency and Euro-weighted efficiency are usually given in the inverter data sheet, which is determined at STC. The usage of these data sheet efficiencies is not realistic because the inverter rarely functions at STC. The weighted efficiency takes into consideration the inverter's exposure to climate changes and the irradiance profile, since the irradiance is proportional to the inverter input power and the inverter efficiency differs according to the power classes of operation. So, the weighted efficiency is a sound characterization of the inverter efficiency due to its conformity to the working conditions.

III. FORMULATION OF WEIGHTED EFFICIENCY

Calculation of the inverter weighted efficiency is conducted according to in the IEC 61683:1999 Standard [3]. This standard recommends that the weighted efficiency formula should be derived with the use of the PV emulator, which emulates the output of the actual PV ad inverter system. The emulator is fed by one-year irradiance data and the input and output power to the inverter are recorded. The main assumption is that the panel's temperature is kept constant at 25 ^{o}C. The irradiance is made variable to compare the inverter efficiency when tested in different environmental conditions [5].

The weighted average energy efficiency (η_{WT}) of the inverter is based on the irradiance-duration curve for an ON-grid connected inverter, which has no storage, and the reverse power flow is accepted and allowed. On the contrary, the weighted efficiency determination documented on the load power-duration curve in case of stand-alone or off-grid operation of the inverter, which has a storage subsystem and some of the generated power is dissipated in the inverter and batteries.

The formula for the weighted energy efficiency (η_{WT}) of the on-grid operation of the inverter is determined as the summation of the inverter efficiency product of each irradiance operation class and the debating weightage factor (K_i). The weighted factor is related to the sum of time (T_i) that the inverter works at an irradiance class by the whole duration time (T_{WT}) of the inverter actuation. By using T_i as the duration of the DC input to the inverter power class (P_{dci}) or irradiance class (I_i), P_{outi} as the output power class, η_i as the inverter efficiency at class i, then the inverter weighted efficiency is defined as [3]:

$$\eta_{WT} = \frac{\sum P_{outi} \cdot T_i}{\sum P_{dci} \cdot T_i} \quad (2)$$

$$= K_1.\eta_1 + K_2.\eta_2 + K_3.\eta_3 + \cdots + K_n.\eta_n \quad (3)$$

$$K_i = \frac{P_{dci} \cdot T_i}{\sum P_{dci} \cdot T_i} \quad (4)$$

where K_i is the weigh coefficient for each DC input or irradiance level of operation i. If the irradiance-duration curve is given as shown in Figure C.1 in [3], the weighted efficiency of the on-grid inverter can be written as [3]:

$$\eta_{WT} = \sum_{i=1}^{n} \frac{i.T_i}{T_{WT}} . \eta_{i\%} \quad (5)$$

where n is the number of irradiance levels, $\eta_{i\%}$ is the efficiency of the inverter when its DC input power or irradiance is the $i\%$ of its rated value.

$$T_{WT} = 1.T_1 + 2.T_2 + 3.T_3 + \cdots + n.T_n \quad (6)$$

The weigh factors K_i in (4) can be written as:

$$K_i = \frac{i\,T_i}{T_{WT}} \quad (7)$$

IV. A REVIEW ON INVERTER WEIGHTED EFFICIENCY

Up to date, the most used weighted efficiency for energy yield determination is the η_{EURO}. It is formulated regarding inverters working in European areas that accept moderate irradiance penetration and it is given by [6]:

$$\eta_{EURO} = 0.03 * \eta_{5\%} + 0.06 * \eta_{10\%} + 0.13 * \eta_{20\%} + 0.1 * \eta_{30\%} + 0.48 * \eta_{50\%} + 0.2 * \eta_{100\%} \quad (8)$$

The η_{EURO} has six levels of operation: 5%, 10%, 20%, 30%, 50%, and 100%. The irradiance divided by the rated minus the irradiance forms the class of booting, and its values are shown in Table I. The highest weigh factor 0.48 occurs at the 50% operation class, which means that for half of the operation time, the inverter works at 50% of its rated power. The California Energy Commission inverter weighted efficiency (η_{CEC}) [7] has become a demotic pointer to specify the inverter rendition in regions with high irradiance levels [6].

Analogous to η_{EURO}, η_{CEC} has six classes of operation and each class imposes a different value of weigh factor:

$$\eta_{CEC} = 0.04.\eta_{10\%} + 0.05.\eta_{20\%} + 0.12.\eta_{30\%} + 0.21.\eta_{50\%} + 0.53.\eta_{75\%} + 0.05.\eta_{100\%} \quad (9)$$

TABLE I. RANGE OF BOOTING AND WEIGH FACTOR FOR EACH CLASS OF OPERATION

Booting class (%)	Booting range	Weigh factor
5	0-7.5	0.03
10	7.5-15	0.06
20	15-25	0.13
30	25-40	0.10
50	40-75	0.48
100	> 75	0.2

By comparing (8) and (9), the η_{CEC} is further depended on the efficiency of the irradiance levels that the inverter operates. Apart from η_{EURO} and η_{CEC}, there were other formulations of inverter weighted efficiency according to respective local environmental climate changes, such as Izmir efficiency (η_{IZM}) in Turkey [8-9], Chennai weighted efficiency (η_{CHE}) in India [10], Kanpur weighted efficiency (η_{KAN}) in India [11-13], Brazilian weighted efficiency [14-15], and Equatorial weighted efficiency (η_{EQUA}) [16].

Unluckily, the procedures of these weighted efficiency calculations do not comply with the ICE61683:1999 standard, in which the efficiency must be determined by the SPV generated power fed by the regional irradiance profile at constant temperature to the emulator. In reality, both irradiance and temperature vary and the irradiance was horizontally estimated, which did not obey with IEC61683 [3]. Also, due to climate variations, those studies are used as case studies for each related city.

V. METHODOLOGY OF INVERTER WEIGHTED EFFICIENCY FOR BAGHDAD CITY (η_{BAG})

Baghdad is a city located in the southwest of the Asia continent at 33°13' N latitude, 44°13 E longitude, and 34 m altitude. The climate of Baghdad is marked as BWH: subtropical desert with dry and hot arid climate [9]. We can suppose that the accurate performance of SPV inverter systems operating in subtropical climates differentiates from the performance of those tested in other climates. This work assumes that η_{max} and η_{EURO} given in the inverter data sheet in Table II are unusable for the energy yield estimation of inverters installed out of the European or Equatorial climates. Therefore, a fangled weighted efficiency formula for SPV inverter in subtropical (Baghdad) climate is derived. To obtain this objective:

- One-year irradiance data from a weather station located in Baghdad city [17-18] were considered.
- The SPV inverter type SMA-4000-SB-TL was run with the SPV array emulator using the combined irradiance-time profile data.
- The input and output power of the inverter were calculated.
- The Baghdad weighted efficiency (η_{BAG}) was calculated.
- The η_{BAG} was validated by using the measured data of one year for the system energy yield (E_{sys}) and the total measured energy with that calculated in (1) was compared using η_{BAG}, η_{max}, and η_{EURO}, to show the difference between these calculations and the actual measurements.

TABLE II. SPECIFICATIONS OF SMA-SB-4000-TL-21 SPV INVERTER

DC Input	
	SB 4000TL-21
Maximum DC power cos $\varphi = 1$	4200 W
Maximum input voltage	750 V
MPP voltage range	175 V to 500 V
Rated input voltage	400 V
Minimum input voltage	125 V
Initial input voltage	150 V
Maximum input current, input A	15 A
Maximum input current, input B	15 A
Maximum short-circuit current per input*	20 A
Maximum reverse current from the inverter in the system for max. 1 ms	0 A
Number of independent MPP inputs	2
Strings per MPP inputs	2
Overvoltage category following IEC 60664-1	II
*Input following IEC 62109-2: I_{SCPV}	
AC Output	
	SB 4000TL-21
Rated power at 230 V, 50 Hz	4000 W
Maximum apparent AC power	4000 VA
Rated grid voltage	230 V
Nominal AC voltage	220 V / 230 V / 240 V
AC voltage range*	180 V to 280 V
	SB 4000TL-21
Nominal AC at 220 V	18.2 A
Nominal AC at 230 V	17.4 A
Nominal AC at 240 V	16.7 A
Maximum output current	22 A
Total harmonic distortion of the output current with total harmonic distortion of the AC voltage < 2% and AC power > 50% of the rated power	≤ 4%
Inrush current	< 20% of the nominal AC for a maximum of 10 ms
Maximum output current under fault conditions	34 A
Rated power frequency	50 Hz
AC power frequency*	50 Hz / 60 Hz
Operating range at AC power frequency 50 Hz	45 Hz to 55 Hz
Operating range at AC power frequency 60 Hz	55 Hz to 65 Hz
Power factor at rated power	1
Displacement power factor cos φ, adjustable	0.8 under excited to 1 to 0.8 overexcited
Feed-in phases	1
Connection phases	1
Overvoltage category as per IEC 60664-1	III
* Depending on the configured country data set	
Efficiency	
	SB 4000TL-21
Maximum efficiency, η_{max}	97.0%
European weighted efficiency, η_{EU}	96.4%

To formulate the weighted efficiency of the grid-connected SPV inverter in the subtropical climate of Baghdad, a fangled set of weigh factors must be determined according to the IEC83:1999. However, the irradiance classes (levels) are aggregated into seven classes of operation according to the irradiance-duration curve produced by the SMA-4000-SB-TL inverter operated in Baghdad, as displayed in Figure 1, which was erected from one-year irradiance data of Baghdad weather station [17-18]. The period for each class is respectively T_1, T_2, ……, T_7. The weigh factor for each level can be seen in Figure 1 and (6) and (7) as illustrated in Table III. The weighted efficiency of the inverter is calculated by (3). Figure 2 shows the relation of inverter DC input power levels with inverter efficiency. The weighted efficiency values are given in Table III. From Table III, the inverter η_{BAG} is 91.8% while from Table II of the inverter data sheet, the η_{max} is 97% and η_{EURO} is 96.4%. An inverter that is 1% less efficient is deduced to be 10% cheaper than other inverters [19-24].

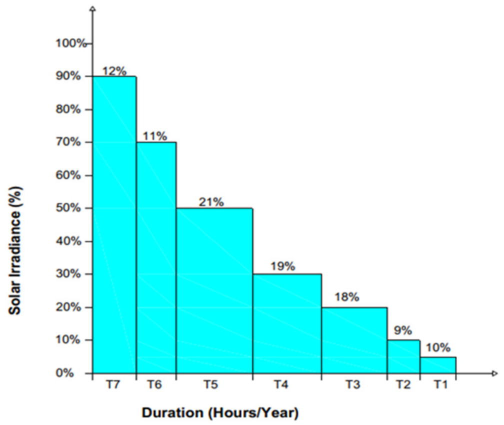

Fig. 1. Solar irradiance-duration curve in Baghdad city.

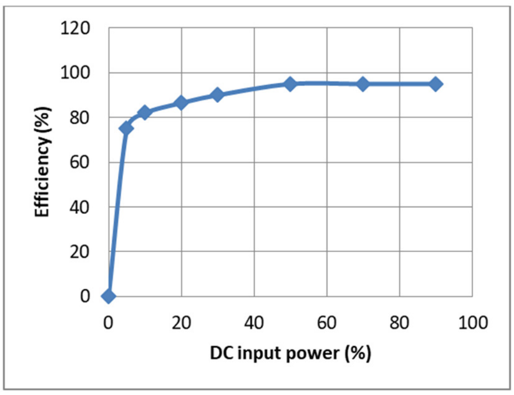

Fig. 2. DC input power levels vs inverter efficiency.

TABLE III. ON-GRID SOLAR PV INVERTER WEIGHTED EFFICIENCY

Solar irradiance (%)	Inverter efficiency (%)	On-grid weigh factor	On-grid inverter weighted efficiency (%)
5	75	K_1= 0.0237	1.77
10	82	K_2= 0.0459	3.76
20	86	K_3= 0.1290	11.1
30	90	K_4= 0.1836	16.52
50	95	K_5= 0.2600	24.70
70	95	K_6= 0.1570	14.91
90	95	K_7= 0.2008	19.07
Total Weighted Efficiency			91.8 %

VI. RESULT VALIDATION

Since the temperature is rarely constant during the system operation and the weighted efficiency is derived at constant temperature, the result of η_{BAG} must be validated. The annually measured energy yield of the system (E_{sys}) throughout the year 2022, as shown in Figure 3, can be compared with the calculated energy yield using η_{BAG}, η_{max}, and η_{EURO} in (1).

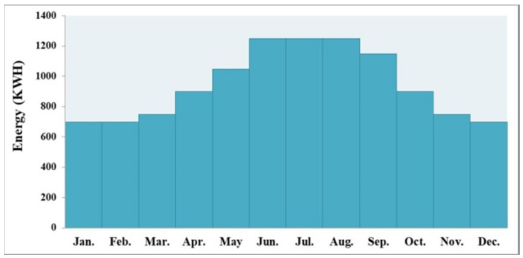

Fig. 3. Yearly measured energy (KWH) produced by SMA-4000-TL.

To determine the E_{sys}, the number of sun hours in one year is (3380) [25], P_{array} is equal to 4.0 Kw, f_{temp} is equal to 98%, f_{mm} is equal to 96%, f_{dirt} is equal to 97% and η_{cable} is equal to 98%. These values make error to be less than 0.8% and are verified in [1]. The η_{inv} is varied using either η_{BAG}, η_{max}, or η_{EURO}. Table IV shows the results of the three computed energy yields, and from the comparison with the measured energy, it is clear that η_{BAG} is the best option to represent the inverter efficiency with only a 1% difference between calculated and measured energy. The real SPV system is a 4 kW roof-top grid-connected system with the SMA-4000-SB-TL inverter. The results show that every region in the world must have its inverter weighted efficiency and SPV system energy calculations to get the correct payback duration and RoI.

TABLE IV. RESULTS OF E_{sys} CALCULATION FOR VARIOUS SPV INVERTER EFFICIENCIES

Efficiency	Efficiency percentage (%)	Calculated E_{sys} (kWh)	Measured E_{sys} (kWh)	E_{sys} divergence (kWh)	E_{sys} divergence (%)
η_{BAG}	91.8	11483	11350	133	1%
η_{max}	97.0	12147	11350	797	7%
η_{EURO}	96.4	12071	11350	721	6%

VII. CONCLUSION

Due to the fact that any region has its own irradiance profile, the SPV inverter weighted efficiency is affected by the irradiance-duration curve, hence, Baghdad weighted efficiency (η_{BAG}) is derived in this paper to best represent the real inverter efficiency in the specific subtropical region, based on the IEC61683:1999 Standard. The derived formula was further validated when it calculated the energy yield of the SPV system ($E_{sys-cal}$), which was compared with the measured energy yield of the system for one year data of a real grid-connected type SMA-4000-SB-TL inverter. The comparison shows that the $E_{sys-cal}$ with η_{BAG} instead of η_{max} or η_{EURO} (given from the data sheet of the inverter) matches the real measured energy yield ($E_{sys-mea}$) more closely with only a difference of 1% between the calculated and the measured values. This means that the use of η_{BAG} instead of the efficiency given in the inverter data sheet (η_{max} or η_{EURO}) in the determination of the energy yield of the system will describe the predicted output power from a constructed SPV system and will more accurately forecast the payback duration and return of investment.

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