Performance Analysis of Grid-Connected CIGS PV Solar System and Comparison with PVsyst Simulation Program

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Abstract- CIGS is the thin film technology (second generation) fabricated from Copper-Indium Gallium Selenide. This research displays the performance assessment of a 5kWp CIGS grid-connected PV Solar system. CIGS system installed at al-Mansour Company, Iraq-Baghdad (latitude 33.3 ° N, longitude 44.4 ° E and 41m above the sea level). The current paper presents the performance analysis of CIGS system (real system) and the comparison with PVsyst simulation program to find out how close are the CIGS system approaches perfect system (PVsyst) under Baghdad climate. The CIGS system was monitored during the year of 2017. The daily average of array, reference and final yields for real and PVsyst systems were 5kWh/kWp (h/day), 6.1kWh/kWp and 4.85kWh/kWp**,** and 5.46kWh/kWp (h/day), 6.3kWh/kWp and 5.3kWh/kWp respectively. The annual energy yield from real and PVsyst systems are 1781.8kWh/kWp/year and 1924kWh/kWp/year respectively. The annual energy output from real and PVsyst systems are 8820.2kWh and 9538.5 kWh respectively. The annual global horizontal solar irradiation (GHI) received in Baghdad of 1986.4kWh/m^2. The yearly daily average of system and array losses for real and PVsyst systems were 0.18 kWh/kWp/day and 0.18 kWh/kWp/day, and 1.1kWh/kWp/day and 0.84 kWh/kWp/day respectively. The yearly average of array, system and inverter efficiencies for real and PVsyst systems were 12.7%, 12.1% and 96.47%, and 13.18%, 12.72 and 97 respectively. The yearly average of the capacity factor and performance ratio for real and PVsyst systems were 20.4% and 80.2%, and 22% and 83% respectively. These values indicate very good performance for CIGS PV solar system fixed in Baghdad city. The comparison between PVsyst and CIGS will take place in results and discussion.

Keywords Grid-connected, CIGS, Solar PV, performance , PVsyst, solar cell.

1. Introduction

Solar energy is a green energy, which can be used to accomplish worldwide energy needs. The energy demands are increasing while the fossil fuel resources which dominate most general energy systems are limited and forecast to become less and more expensive in future [1]. Renewable energy resources exist over wide geographical areas, in contrast to other energy sources, which are concentrated in a limited number of countries like oil and gas. Rapid deployment of renewable energy and energy efficiency is resulting in significant energy security, climate change mitigation, and economic benefits. The transition from first generation technology silicon solar cells to the second generation (CIGS) cells (thin film technology) is a quantum leap in the field of photovoltaic production. The materials of PV solar panels comprise: the Crystalline Silicon (polycrystalline and Monocrystalline), (Amorphous silicon (a-Si), Copper-Indium Gallium-Selenide (CIGS), Cadmium Telluride (CdTe)). Silicon panels make up the largest part in the market, with an estimation of 90% of market share of panels while thin films make up less than 10% [2]. PV solar cells made of silicon are commonly called first generation technology. The market at current is on the brink of transferring to technology of a second generation (thin film). Technology of Thin film introduces more benefits as a big drop in material costs in comparison with the costs of the silicon wafers that need, as well as, thin film solar PV cells Technology have little temperature coefficient[3]. Silicon solar cells efficiency at standard test conditions (1000W/m^2, 25°Cand AM: 1.5) close to 24.4% for Monocrystalline, 19.8% for a polycrystalline and 10.2% for amorphous [4, 5, 6], while efficiency of (CdTe) and (CIGS) are 16.5% and 19.9%, respectively [7,8]. More researches were conducted throughout the world, about the performance analysis and characteristics of the on-grid PV solar systems, for example Li studied an On-grid PV system in city of Hong Kong and proved that the energy payback duration was about 8.9 years [9]. Canete et al. studied four different PV panel technologies which are CdTe, amorphous silicon, polycrystalline silicon, and microcrystalline silicon and estimated of incoming solar radiation for a year in Spain and it showed that the thin-films were more productive than other panels [10]. Mabvuto. M , Kivanc .B, Numan .S , Kolay .Ü, were conducted a research about Comparative Performance Analysis of 20kWp Grid Connected for different PV solar Technologies (CIS, C-Si, CdTe) in Zambia, The results showed that CdTe has higher performance of 80.17%, followed by CIS of 73.97%, and C-Si the least of 72.24%. the monthly average solar irradiation of 167 kWh/m2 with the annual average temperature of 26Co [11].Naseer, et al. conducted a research about the evaluation performance through depositing and the treatment of dust by tracking the panel and they found that when the tracker panel bend down to capture the solar radiation at sunset the dust deposits down because of gravity [12,13,14]. Shaharin .A, Atul .K, Mior .M, Mohammed .A, were conducted research about Influence of Dirt Accumulation on Performance of PV Panels, and they found that the external resistance could reduce the photovoltaic performance by up to 85%[15]. The main goal of this research is to assessing the performance of 5kWp CIGS (thin film) grid-tied PV system in a one year under Baghdad-Iraq climate conditions.

2. Real and simulation PV solar system details

PVsyst simulation program has same real options in terms of location, nominal power, tilt angle, azimuth angle, latitude, longitude and panel technology. The PV solar system lies in north Baghdad/Al-kadhumia city in Al-Mansour Factory in latitude 33.3^{O}N and longitude 44.4^{O}E.

Table 1.Real and PVsyst solar PV system details

System	*Simulation System*	*Real System*
Panel model	TS-165C2 CIGS	TS-165C2 CIGS
panels Number of	30	30
Inverter model	SMA SB-5000T-21	SMA SB-5000T-21
Inverter Size (kWp)	5.30	5.30
Inverter efficiency	97%	97%
System Size (kWp)	5	5
Tilt Angle	15/50 Sum/win	15/50 Sum/win

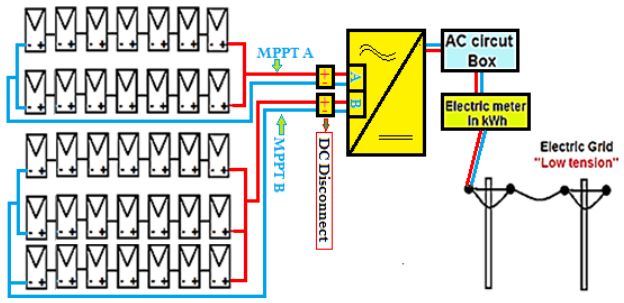

FIG 1. Single line diagram of CIGS grid-connected PV solar system.

FIG 2. 5kWp CIGS grid-connected PV solar system.

3. Performance Analysis

Assessment parameters include: losses (System and Array losses), yields (Final, Array and Reference yield), System Efficiencies (Inverter Efficiency, Array Efficiency and System Efficiency), Capacity Factor, Performance Ratio and Energy produced.

3.1. System yields

The system energy yields are divided into three kinds which are Reference yield, Final yield and Array yield. The array yield Y_A can be defined as the direct current (DC) energy produced by the PV solar array divided by nominal (rated) PV solar system power. It represents the time at which the system operates in its rated power in unit of kWh/kWp [12].given as following:

$$Y_A = \frac{E_{DC}}{P_{PV,rated}} \; (kWh/kW_p) \ldots\ldots\ldots\ldots (1)$$

Where: E_{DC} represents the direct current Energy production in unit of (kWh). While the **Final yield (Y_F)** is the AC energy produced via the PV solar system for a specific duration over the nominal (rated) power value of PV solar system [16]. It represents the time at which the system operate in its rated power in unit of kWh/kWp. given as following:

$$Y_F = \frac{E_{AC}}{P_{PV,rated}} (kWh/kW_p) \ldots\ldots\ldots\ldots (2)$$

Where: E_{AC} represents the alternating current energy product (AC Energy) in unit of (kWh). while **The Reference Yield Y_r** is defined as the global irradiation in-collimated plane divided by the reference irradiance that equal to 1kW/m^2. The Reference yield is given as:

$$Y_r = \frac{H_T}{H_R}\ (kWh/kW_p) \qquad (6)$$

Where: H_T and H_R are the solar irradiation in-collimated plane and reference Irradiance respectively.

3.2. System and Array Energy losses:

Array losses (L_A) are show the losses caused by array working that exhibit disability of the array to totally convert the available solar insolation (irradiation) to electricity. The array losses are the difference between the Y_R and the Y_A. It is calculated as [16]:

$$L_A = Y_R - Y_A (kWh/kW_p) \qquad (4)$$

The system energy losses (L_S) are caused by losses in converting the direct current energy to alternating power (DC to AC) via the inverter. It is calculated as:

$$L_S = Y_A - Y_F (kWh/kW_p) \qquad (5)$$

3.3. System Efficiencies

The PV solar system efficiency is classified into following: Array, System and Inverter Efficiencies. these efficiencies can be calculated annually, monthly, daily and hourly. The system efficiency (ηsys) is built on the alternating current power product and the array efficiency (ηPV) is built on the direct current power product. The array efficiency is the ratio The array efficiency is the ratio of daily, monthly or annually average of array energy product (DC) to the total daily, monthly or annualy average of solar irradiation in-collimated plane multiplied by the area of the PV solar array [16]. The PV solar array efficiency is given as:

$$\eta_{PV} = \frac{100 * E_{DC}}{H_t * A_m}\ \% \qquad (6)$$

where A_m = array area (m^2), Ht = solar irradiation in-collimated plane. it is calculated as:

$$\eta_{SYS} = \frac{100 * E_{AC}}{H_t * A_m}\ \% \qquad (7)$$

The inverter efficiency is calculated as:

$$\eta_{INV} = \frac{100 * E_{AC}}{E_{DC}}\ \% \qquad (8)$$

3.4. Performance Ratio (PR)

(PR) appear all PV solar system losses. Value of PR shows how close system approaches perfect performance through actual work and permits comparison of Photovoltaic solar systems each other irrespective of angle, tilt,orientation, location and their rated power capacity [17]. PR is calculated as the ratio of the (**Y_F**) over (**Yr**) of the PV solar system, it given as[18].

$$P_R = \frac{Y_F}{Y_r}\ \% \qquad (9)$$

3.5. Capacity Factor (CF)

CF is a way used to assess the energy produced by an PV solar system and is calculated as the ratio of Alternating Current energy produced by the photovoltaic solar system divided by a specfied duration (usually month or one year) multiplied by rated value (nominal) of the PV solar system. The yearly capacity factor of the PV solar system is calculated as following [18]:

$$C_F = \frac{E_{AC}}{P_{PV,rated} * 8760} \qquad (10)$$

3.6. Energy Output

The overall energy is defined as the quantity of AC power produced by the PV solar system in a specified duration. The hourly, daily and monthly energy product is calculated respectively as follow :[19]

$$E_{AC,h} = \sum_{t=1}^{60} EAC,t \qquad (11)$$

$$E_{AC,d} = \sum_{h=1}^{24} EAC,h \qquad (12)$$

$$E_{AC,m} = \sum_{d=1}^{N} EAC,d \qquad (13)$$

Where: $E_{AC,t}$ is AC Energy produced at minutes; $E_{AC,h}$ is AC Energy produced at hour; EAC,d is AC Energy produced at day; $E_{AC,m}$ is the monthly AC Energy produced and N represent the days number in the month.

3.4 Real and PVsyst Data

Table 2 content real and PVsyst data are used in this manuscript. In this table is noticed the data values of PVsyst system lager than real system that because PVsyst system not effects in atmospheric phenomena like cloud ,rain and dust.

Table 1.Real and PVsyst solar PV system Data

PVsyst System Details					**Real System Details**			
Month	**T Amb** °C	**GlobInc** kWh/m²	**E_Grid** kWh	PR%	**GlobInc** kWh/m²	**T Amb** °C	**E_Grid** kWh	PR%
January	7.98	156.5	690.3	89.	145.88	16.8	580.02	80.3
February	11.13	164.2	713.9	87.7	156.8	18.5	642.41	82.7

March	16.05	184.0	781.0	85.7	174	23.9	720.92	83.7
April	20.59	194.0	809.7	84.2	183.6	28.8	749.91	82.5
May	26.65	215.9	877.7	82.0	201.1	33.6	789.66	79.3
June	31.40	217.4	865.9	80.3	231.7	40	887.97	77.4
July	34.26	220.2	869.9	79.7	231.1	44	876.15	76.5
August	33.77	223.4	883.6	79.8	223.5	43	871.96	78.8
September	28.74	206.9	835.1	81.5	193	40	765.14	80.1
October	23.84	198.3	820.7	83.5	182.6	34	731.08	81
November	14.70	171.3	737.7	86.9	150	22	601.50	81
December	9.86	148.9	652.8	88.4	141.5	19	560.41	80

Where: GlobInc GlobInc is Global incident in coll. Plane.

T Amb is Ambient Temperature.

E_Grid is Energy injected into grid

PR is Performance Ratio

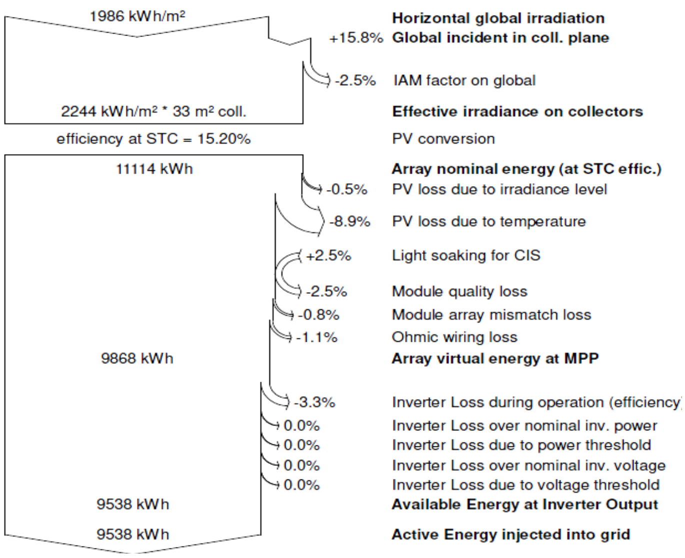

FIG 3. Loss diagram over the whole year

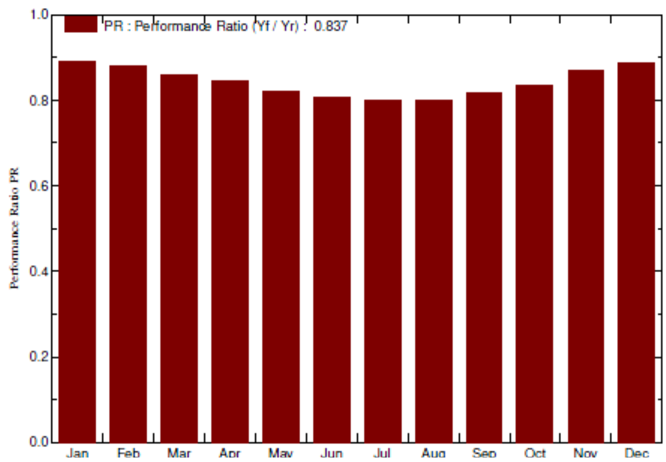

FIG 4. PVsyst Performance Ratio

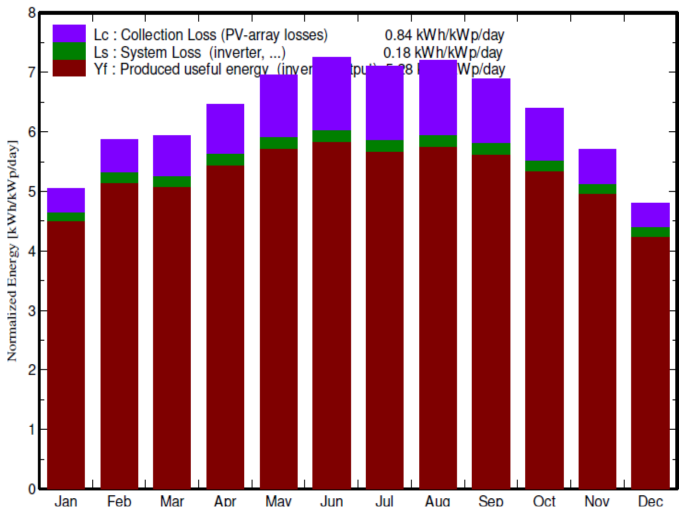

FIG 5. Losses and Final Yield

figures details (4 and 5) are discussed and mentioned in abstract and, results and discussion.

4. Result And Discusion

Fig 6 illustrates the monthly generated electrical energy and the solar insolation in collimated plane. In December the lowest value of the generated electrical energy was 586.113kWh because of the clouds, rain and low solar radiation intensity, while the highest energy generated was in June which is 882.778kWh because of the clear sky , high intensity, solar radiation and the long day. The solar irradiation (reached PV system) differs from 4612.6kWh in December 2017 to 7553.4kWh in June 2017. The lowest values of solar irradiation was within the cloudy and rainy duration while the highest value was in the arid summer duration. In the period of 12 months the energy produced was 8820.204 kWh where the monthly average of 735kWh. The total energy generated through 12 month over the nominal power value of the CIGS solar system is 1781.8kWh/kWp. The monthly average of maximum temperature typically vary from 44°C in July to 16.8°C in January , while the annual average of maximum temperature was 30°C. In spite of the high temperature in June which in turns reduce the energy produced from the PV solar system, this month it has the highest value of electrical energy produced because it has the largest number of sunrise hours (15 hours) and highest intensity of solar radiation. In the other side, the lowest value of electrical energy produced was in December because it has the lowest number of sunrise hours (9 hours) and lowest intensity of solar radiation. In comparison, the annual average of energy produced from CIGS PV solar system (real system) which equal to (8820.204 kWh) at annual average of ambient temperature (30ºC) with the ***PVsyst simulation program which is the clear sky model and it is a software package used for the data analysis, sizing and study of completed PV solar systems. PVsyst deals with DC-grid, grid-tied, stand-alone, and pumping and PV solar systems. This software comprise spacious of meteorological databases, PV solar Systems Components databases and add to general solar energy Tools*** . PVsyst version was used in current study is 6.5.1. [20]. The annual average of energy produced from the simulation program (PVsyst) was (9692kWh) at annual average of air temperature of 21.5ºC. Obviously the difference is not great although the real system works at high temperatures and is affected by rain, cloud and dust in the contrary of PVsyst simulation program results which are built on low temperatures and they are not affected by rain, cloud and dust, this means the practical measurement results were very good because they are very close to PVsyst simulation results.

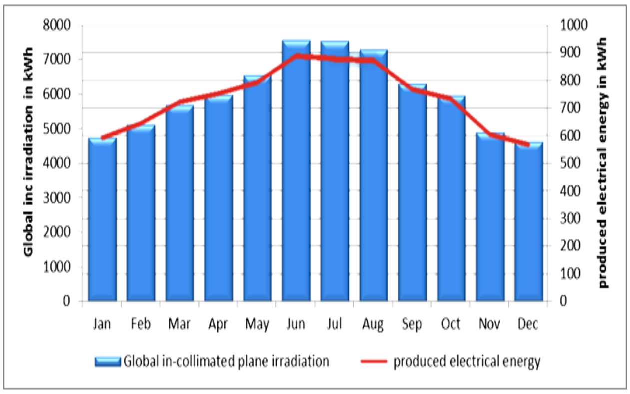

Fig 6.Monthly product of electrical Energy and Solar irradiation in-collimated plane of real system.

The monthly average values of array yield, final yield and daily reference yield were presented in Fig 7. It can be noticed that the lowest values were documented in winter duration in December and January. In December 2017, the array yield ,final yield and reference yield were 4.1kWh/kWp/day,3.9kWh/kWp/dayn and 4.7kWh/kWp/day, respectively while the highest values of array yield, final yield and reference yield were in June of 6.13kWh/kWp/day, 5.9kWh/kWp/day and 7.72kWh/kWp/day respectively. The annual average of array yield, final yield and reference yield for throughout of 2017 year were 5kWh/kWp/day,4.85kWh/kWp/day and 6.1kWh/kWp/day respectively. Vignola et al.[21] noticed that inverter efficiency drops nearly 1% for about each 12°C rise in air temperature. when comparing the final yield of real system at annual average temperature during the course of a 2017 year which is 30ºC with the final yield of simulation program (PVsyst) at annual average temperature during the course of a 2017 year which is 21.5ºC,It was found that the annual average of the final yield of CIGS system and simulated results for the period of 2017 were 4.85kWh/kWp/day and 5.33kWh/kWp/day respectively, this shows small difference between CIGS system and PVsyst system. This simulation program it is a clear sky model so it doesn't taking the effect of the atmospheric condition as dust, cloud and rain in consideration, However, the PV solar CIGS system works very well under the Baghdad climate and can be considered a promising technology for use in Iraq despite the hot climate of Iraq in the summer.

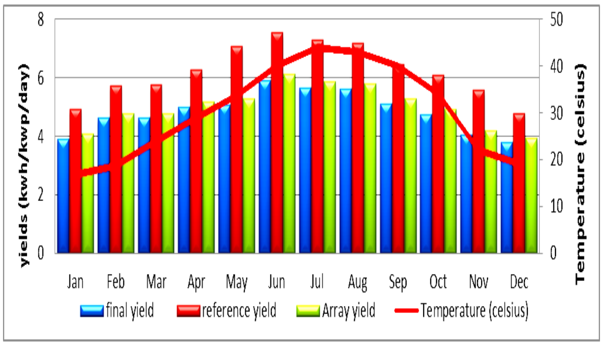

Fig 7. Monthly average of daily yields of real system.

Fig.8 illustrates the monthly average of daily losses to overall, array and system. In July, it was noticed that the maximum value of monthly average of daily array losses of 1.6kWh/kWp/day that due to high air temperature and the minimum value which was recorded in the January and December months of 0.61kWh/kWp/day, these values make up 21.4% and 12.9% of the monthly daily average of reference yield respectively. Losses in the system (represent inverter losses) diverse from 0.14 kWh/kWp/day in December to 0.22 kWh/kWp/day in June, as displayed in Fig.4, that because of large conversion from DC to AC current due to a large solar irradiance intensity incident on panels in June .These values make up 3% and 2.9% of the daily reference yield respectively. When it is compared, the yearly average of daily array losses of the real system of 1.1kWh/kWp/year at yearly average of air temperature of 30ºC with daily array losses value of PVsyst simulation program of 0.722kWh/kWp/year at yearly average air temperature of 21.5ºC, It was found that the difference is only 0.47 kWh/kWp/year . the yearly average of daily system losses for real system and simulated system were 0.181kWh/kWp/year and 0.18kWh/kWp/year respectively, this convergence in daily system losses between real and simulated systems due to approaching the inerter efficiencies to two systems because inverter of real system was installed indoor. The maximum value of overall losses was recorded in July of 1.82kWh/kWp/day and the minimum value was recorded in January and December of 0.77kWh/kWp/day, These values make up 24.4% and 16.8% from daily reference yields respectively. The yearly average of daily losses to overall, array and system were 1.3kWh/kWp/day, 1.1kWh/kWp/day and 0.194kWh/kWp/day, respectively. Overall losses equal (array losses + system losses).

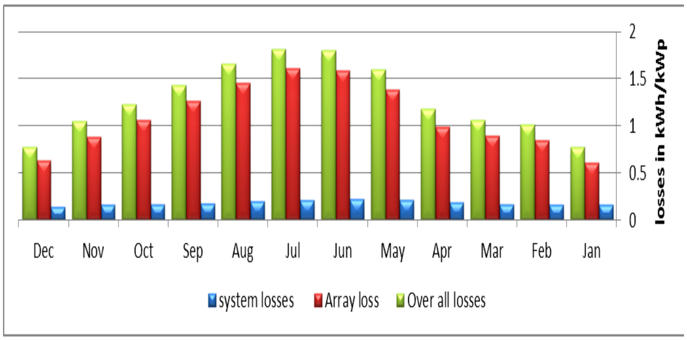

Fig 8. Monthly average of daily losses to overall , array and system of real system.

Fig.9 shows The monthly average of inverter, system and array efficiencies during the observing duration. The annual average values of efficiencies are 96.6%,12.1% and 12.7% respectively. A maximum value of the inverter, system and array efficiency were in January of 96.7% ,12.7% and 13.1% respectively and the minimum efficiency of inverter, system and array were in July of 96.6%, 11.5% and 12% while the annual average of inverter, array and system efficiency of PVsyst simulation program at annual average temperature 21.5ºC were 97% 13.16% and 12.72% this means the measured results (real data) are very close to PVsyst results in spite of the CIGS system works at annual average temperature of 30ºC.

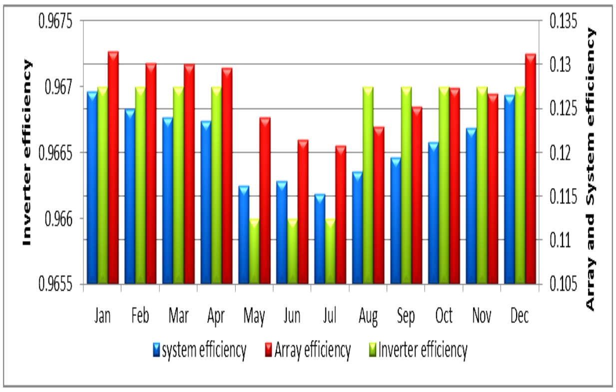

Fig 9. Monthly average of inverter, system and array efficiency of real system.

Fig. 10 shows the monthly average capacity factor and performance ratio. The yearly average of PR for the real system was 80.3% where the maximum value of PR was in January and December of 83.8% and the minimum value was 76% in July month.PR is indicator for how near the real system from perfect performance through actual operating [22].The PR of the present system drop in month May, June, July and August under the average due to arising temperature in these months. when compared the yearly average PR of the real system which equal to 80.3 at annual average temperature which is 30ºC with annual average performance (PR) of PVsyst simulation program which equal to 83.7% at annual average temperature which is 21.5^{O}C , it was found that the measured PR (real) very close to simulation program PR in spite of the simulation program works at air temperature less than air temperature at which real system (CIGS system) works, so it can be considered PR of real system very well in spite of the high air temperature effect, this means this real system is not significantly affected in high air temperature.

The yearly average of capacity factor (CF) is 20.4%, where the maximum value of 24.8% in June and a minimum value of 16% in December. CF is the indicator exhibits the time magnitude in percentage at which the generation of the PV solar system in maximum capacity, Therefore the system generation in its full capacity roughly 92 days or 2208 h per year (June, July and august). The CF has a direct implication on the cost of electricity generation. Therefore the PR and CF are a very significant parameters to assess grid-connected PV solar systems. In India CF throughout the state contrasts between 20% and16% [23]. In Mauritania capacity factor throughout the country contrasts from a 11.7% to 20.5%[22]. In Malaysia CF of the PV system was 10.47%. in our system the annual average capacity factor varies between 16% and 24.8% this means it is best capacity factor than all mentioned above in spite of arising temperature than all mentioned above and when compared the annual average capacity factor of this real system (CIGS) of 20.3% with the annual average capacity factor of PVsyst simulation program of 22% ,was found that the difference small (only 1.7%) in spite of the real system (CIGS) works at air temperature bigger than at which PVsyst program works and this program not takes cloud, rain and dust into consideration. There is a way used to improve the performance ratio and capacity factor of the PV solar modules by using optical reflectors and cooling [24].

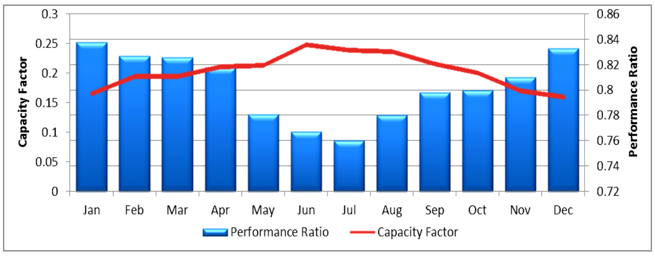

Fig 10. Performance ratio and capacity factor of real system.

5. Conclusion

In current study was found the following conclusions:

- Was found there are small difference between PVsyst simulation program and current CIGS system values in spite of PVsyst works at annual average temperature of 21ºC and CIGS system at 30ºC.
- In the terms of efficiency CIGS system very close to efficiency of PVsyst simulation program as mentioned in results and discussion above and also the losses very close between the two systems.
- The conclusions above illustrate clearly how the CIGS technology results close to PVsyst results, where the PVsyst regard ideal system because it is not affected by cloud, rain and dust and works at annual average temperature of 21.5ºC on the contrary of CIGS system (real measured results) which is affected by cloud, rain and dust and works at annual average temperature (30ºC), this means the real

system (CIGS) is not significantly affected by hot Iraqi climate.

- In the terms of losses there is approaching between CIGS (real) system and PVsyst program in cold season while the difference increases small in hot season namely the overall losses of CIGS becomes slightly bigger than PVsyst.
- According to the four points aforementioned can say that the CIGS technology is promising and very suitable for hotter climates in Iraq and Arabian Gulf.

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