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Efficient Energy Solution: Implementing a Smart PV-Generator Hybrid System for Enhanced Fuel Savings

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Keywords:
On-grid PV system; PV-diesel hybrid system; Energy management system.

Highlights:

- *Smart EMS limits PV penetration to 75%, ensuring 25% min generator load for safety.*
- *Hybrid system achieves 24L/h fuel savings & 50kg/h CO2 reduction vs diesel-only.*
- *PV-generator integration cuts operational costs by 8500 ID/h in practical implementation.*

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Abstract: The present study presents the design and implementation of a PV-generator hybrid system, integrating an on-grid PV system with a 0.5 MW diesel generator. The on-grid PV system, with a nominal power of 135 kW, was located on the top of the Renewable Energy and Environment Research Center building. The hybrid configuration serves as a reliable solution for power outages, seamlessly synchronizing the PV system with a microgrid formed by the generator. To ensure the robust operation of the system and prevent potential damage to the generator, an energy management system card was developed. This card incorporates a Reverse Power Protection Relay, programmed to disconnect one or two inverters, thereby limiting the PV penetration to below 75%. This measure guarantees a minimum generator load of 25%. The practical application of this setup demonstrated its effectiveness in powering building loads, resulting in a noticeable reduction in fuel consumption. The results indicate substantial fuel savings, with the generator demonstrating a 24-litre reduction in fuel gas per hour. This reduction equates to a cost savings of 8500 ID/h and a significant reduction of 50 kg/h in CO_2 emissions. The inverter efficiency observed in this system ranged from 71% to 83%.

حل فعّال لتوفير الطاقة: تنفيذ نظام هجين ذكي يربط منظومة كهروضوئية بمولّد كهربائي لتحسين التوفير في استهلاك الوقود

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الخلاصة

في هذا البحث، تم تصميم وتنفيذ منظومة كهروضوئية هجينة مع مولد من خلال ربط منظومة متصلة بالشبكة مع مولد ديزل سعة 0.5MW. المنظومة الكهروضوئية منصوبة ابتداءا في مركز بحوث الطاقة المتجددة والبيئة وبقدرة تصميمية 135kW. يمكن استخدام هذه المنظومة في حالة حصول قطع في الشبكة الوطنية، حيث يتم اجراء التزامن مع الشبكة المايكروية المتكونة بواسطة المولد. لضمان عمل المولد بحمل واطئ (اقل من 25%) لتجنب عطب المولد، جرى بناء منظومة ادارة طاقة باستخدام جهاز حماية القدر العكسية والذي تمت برمجته بحيث يفصل عاكس او عاكسين لتقليل القدرة المشاركة مع المولد الى اقل من 75%. استخدمت هذه المنظومة لتشغيل احمال المبنى وبينت النتائج توفير كبير بصرف الوقود. حيث وفر المولد بحدود 24 لترا من الوقود في الساعة. هذا يمثل توفير مبلغ 8500 دينار عراقي بالساعة وتجنب تكوين 50kg من غاز CO2 في الساعة. كانت كفاءة العاكس المستخدم في هذه المنظومة قليلة بين 71% و 83%.

الكلمات الدالة: المنظومات الكهروضوئية المتصلة بالشبكة، المنظومات الكهروضوئية الهجينة مع مولد الديزل، منظومة ادارة الطاقة.

1.INTRODUCTION

The worldwide desire to reduce carbon footprint emissions has led to a growing investment in the renewable energy sector, which pushed photovoltaic (PV) technology to become more mature, especially in the last decade [1-3]. As the capital expenditure of PV systems dropped dramatically in the last few years, PV can now provide a practical and economically attractive alternative to electricity generation over fossil fuels [4, 5]. There are three primary types of PV system designs based on the inverter type: off-grid PV systems (also called standalone PV systems) [6], on-grid PV systems (also called grid-tied or grid-connected PV systems) [7], and hybrid PV systems [8]. A hybrid PV system incorporates multiple power generation sources, such as PV combined with a wind generator or PV coupled with a diesel generator, among other possibilities. Therefore, these systems require special inverters capable of integrating diverse energy sources. Examples of hybrid systems are the DC-coupled and AC-coupled configurations, which integrate PV modules with a diesel generator and may optionally incorporate a battery bank [9]. Figure 1 illustrates a scheme of DC-coupled and AC-coupled systems with a diesel generator for energy compensation in DC-coupled and with a diesel generator for grid forming in AC-coupled. These two types of systems include various types of inverters with distinct features [10]. The imperative adoption of these systems stems from the need to minimize fuel consumption and mitigate fuel-related pollution, which is achieved by integrating PV systems with generators.

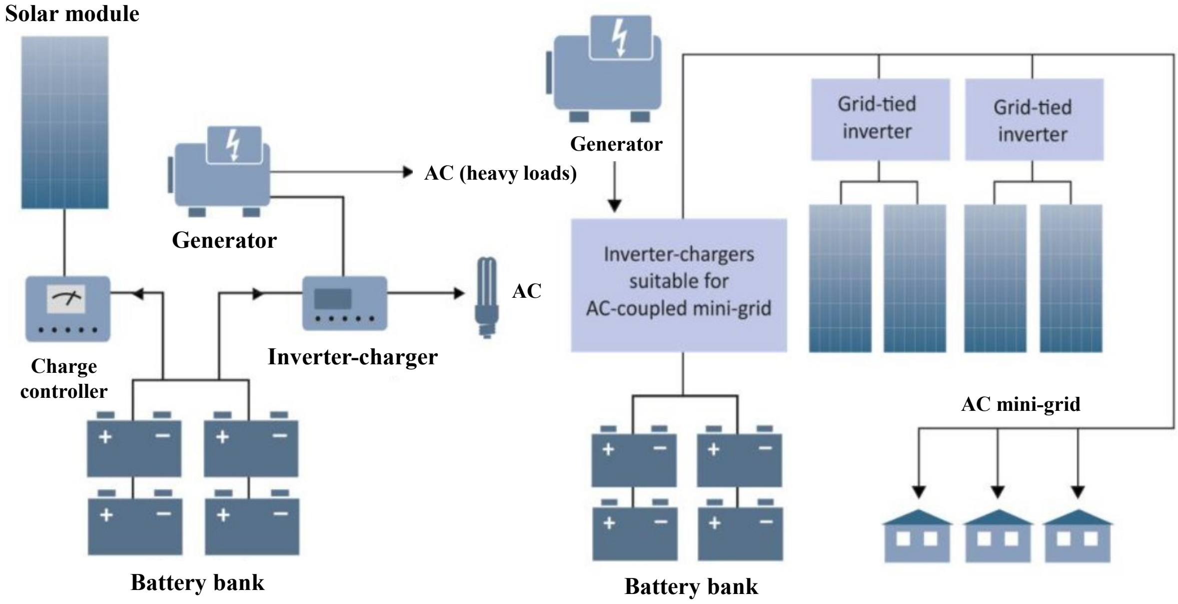

Fig. 1 DC-Coupled System (Left) and AC-Coupled System (Right) [11].

There is a relatively large number of population worldwide with no access or limited access to electricity. An estimated 1.5 billion people worldwide lack access to electrification from the national grid or experience regular grid failures and/or grid shutdowns regularly or even random shutdowns [12]. Moreover, in some regions, extending the national grid may not be economically feasible, especially on islands and in rural areas with complex terrain. In such cases, diesel generators are often used as a convenient and rapid alternative. Recently, off-grid PV systems have become more popular in such regions to reduce fuel consumption [13, 14]. Figure 2 demonstrates the conditions under which a grid extension or off-grid system is the most likely viable option. The given conditions are the length of the grid connection (x-axis) and the required off-grid power capacity (y-axis). For example, if the grid extension is 5 km, all systems smaller than 2.5 kW should be built as off-grids. However, if the required capacity exceeds 25 kW, grid extension would be preferable.

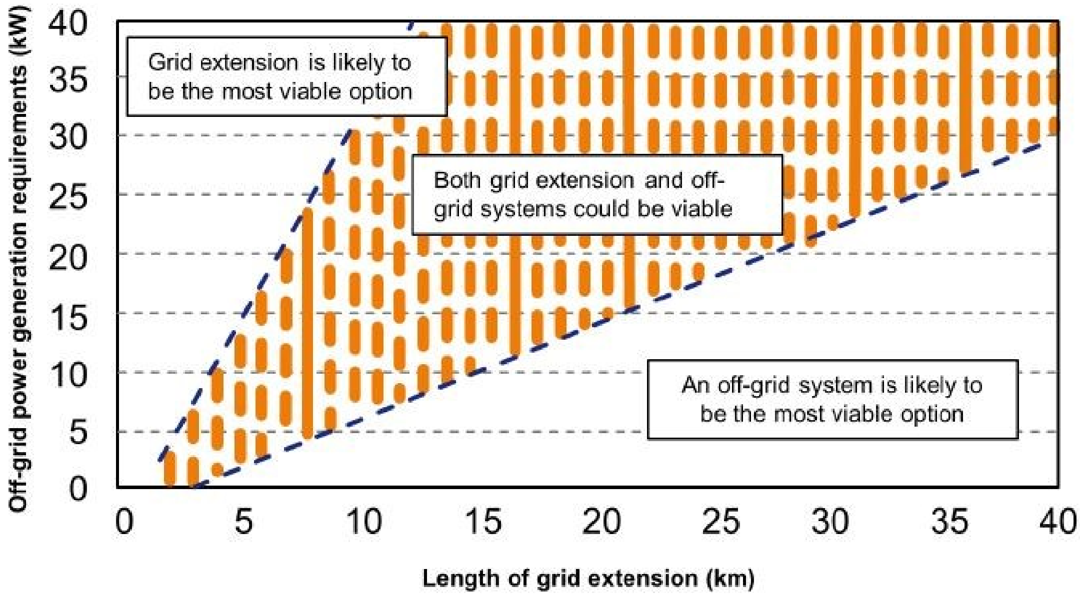

Fig. 2 Viability Limits for Off-Grid and Grid Extension Options [11].

Off-grid PV systems require batteries to maintain a constant electricity supply. However, batteries represent a cost barrier for heavy loads. In this case, using diesel as a backup source is more viable. Diesel generators have been used in conjunction with off-grid PV systems to provide a consistent electricity supply in rural areas, with relatively low fuel consumption and minimal pollution. In this hybrid system, the diesel generator serves as a grid-forming source, enabling the PV system to synchronize and exchange energy with the generator. The concept of microgrids was first used in the United States [15].

1.1.Diesel Generator

In a PV-diesel hybrid system, a low-voltage AC distribution microgrid (an independent grid isolated from the central electricity grid) is formed by combining a conventional generator, e.g., a diesel genset, with a PV system synchronized to this grid-forming genset. PV-diesel hybrid systems fall within the category of off-grid systems; however, they exhibit greater flexibility compared to traditional off-grid setups. Notably, these hybrid systems have the capacity to provide power to relatively high loads without the necessity of incorporating batteries. Eliminating the use of batteries emerges as the most favorable solution in these systems. Batteries, which constitute 50% of the initial cost [16], pose a vulnerability in off-grid PV systems as replacements escalate operational and maintenance expenses. A diesel generator in rural areas is considered a reliable source of energy because diesel generators are a well-proven technology with a relatively low initial investment cost. They also provide high power for heavy loads that PV systems alone struggle to provide. However, the main disadvantage of diesel is that a constant fuel supply is required for off-grid locations, in addition to the high cost of maintenance and pollution issues. Transportation costs to remote locations must also be considered. Therefore, and from the point of feasibility, diesel gensets have low CAPEX (capital expenditure) but high OPEX (operating expenditure). Diesel engines are classified into 2-stroke, 4-stroke, and fuel-injection engines. The 2-stroke engine is cheaper, lighter, more robust, and has a higher power for the same engine size as the 4-stroke (because it has one ignition per revolution compared to one ignition every two revolutions in the 4-stroke). Whereas the 4-stroke engine has a longer lifetime and is less air-polluting. The fuel injection engine is more economical than the 2- and 4-stroke engines and is also most suitable for cold start, but it is noisier.

Diesel generators must operate within a certain range to achieve low fuel consumption. The general performance of a diesel generator varies based on the genset type, genset age, and operation load with respect to the nominal power of the genset. A diesel engine reaches maximum efficiency at the nominal power of the generator. If the generator operates at partial load, its efficiency decreases, e.g., the efficiency drops from 37% when the generator operates at its nominal power to 30% when it operates at 20% of its nominal power, as illustrated in Fig. 3 [17]. Besides, operating at a low load (<25% of the maximum power) can damage the generator. At low load, several consequences occur, including [18]: (i) low cylinder pressure and low engine temperature that cause incomplete fuel combustion, which results in accumulating soot and unburned fuel that clog the piston rings, (ii) oil lubricant burning due to the escape of hot combustion gasses past the piston rings, which results in cylinder glazing, (iii) lower oil performance, and (iv) increased pollution.

1.2.PV-Diesel Hybrid System Concept

To control the PV-to-diesel penetration ratio in a PV-diesel hybrid system, an energy management system (EMS) is required, especially in high penetration ratios (>60%). The EMS ensures a PV penetration ratio of no more than 75% to ensure an operating generator with a capacity of at least 25%. The PV-diesel hybrid system is usually designed with three generators. The EMS balances the penetration by switching one or two generators on and off, with a third generator always on for synchronizing [19]. If only one generator is available on the site, EMS can be programmed to switch the inverters on and off to ensure the proper PV penetration. In the present work, a PV system with a nominal power of 135 kW, consisting of three inverters of 50 kW each, was connected to a 0.5 MW diesel generator through a smart reverse power protection EMS board to form a PV-diesel hybrid system. The board is programmed to turn on and off the inverters to ensure a proper penetration rate and minimize gas consumption and CO_2 emissions as much as possible. The system was installed in the building of the Renewable Energy and Environment Research Center (REERC). Figure 4 shows a conceptual representation of the hybrid system employed in the present study.

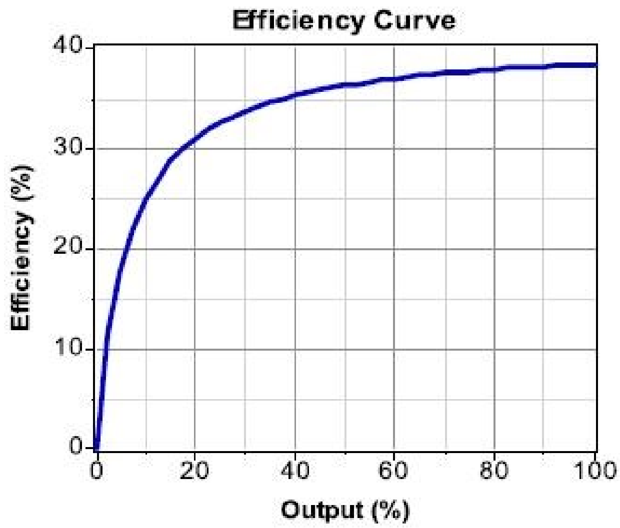

Fig. 3 General Efficiency Curve for the Diesel Generator.

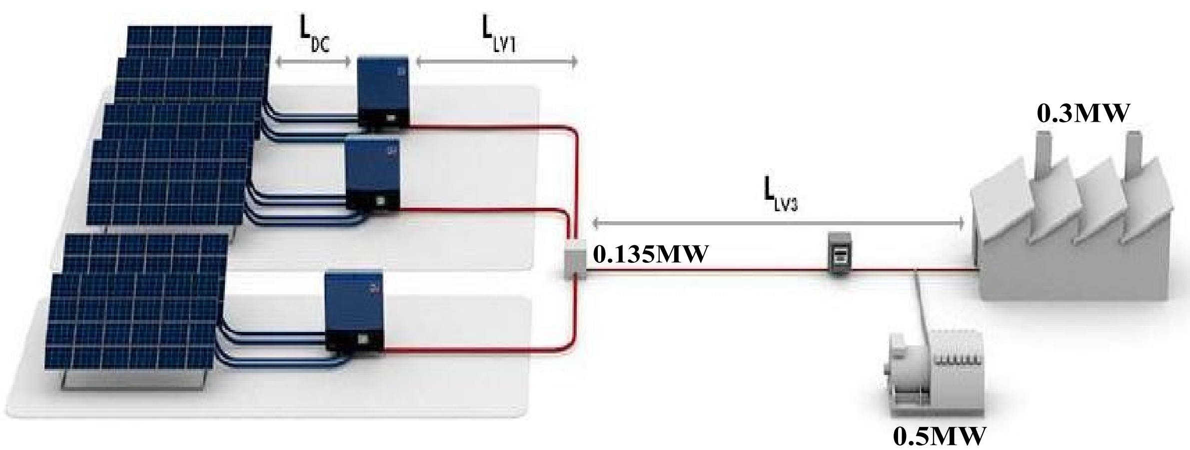

Fig. 4 A Conceptual Image of the PV-Diesel System Used in this Study.

2.EXPERIMENTAL PROCEDURE

A 135 kW on-grid PV system, installed on the REERC building located in Al-Jadriya, Baghdad, consisted of 540 PV panels, each rated at 250 W. The photovoltaic characteristics—maximum power (P_m), short-circuit current (I_{SC}), open-circuit voltage (V_{OC}), current at maximum power (I_m), and voltage at maximum power (V_m)—of a representative PV module were measured under AM1.5G standard testing conditions (STC) using the Keyland Photovoltaic Sun Light Simulator. These measurements are shown in Table 1. The nominal power of the used modules in the datasheet is 275 W; however, the modules are 9 years old and exhibit a 10% degradation. Consequently, the datasheet provides different output values compared to the actual measured outputs.

Table 1 Photovoltaic Parameters of the PV Modules Used.

P_m	250W
I_{SC}	8A
V_{OC}	43V
I_m	7.5A
V_m	36

The system was partitioned into three sets of PV generators denoted as G-A, G-B, and G-C. Each group comprised 180 modules, each with a rated power of 45 kW. Each generator was connected to a 50 kW on-grid SMA inverter of the Tripower CORE1 type. Figure 5 (a) and (b) are photos of the PV system and the inverter used, respectively.

(a) (b)

Fig. 5 (a) A Photograph of the 135 kW PV System on the REERC Building and (b) One of the 50 kW Inverters.

The backup genset used in the building was a 0.5 MW Perkins generator. The building was connected to the grid via a 750 kW (11 kV/0.4 kV) step-down transformer. Switching between the grid and the generator was achieved via a pneumatic changeover. The three inverters were connected to the 0.4 kV feeder behind the pneumatic changeover via AC contactors with an auxiliary circuit, fixed inside a combiner box, so that they could synchronize with either the grid or the generator. EMS is connected to the generator line to monitor the power provided by the generator. It is also connected to the inverter's contactors to switch the inverters on and off depending on the power provided by the generator. Figure 6 shows a flowchart of the designed and implemented hybrid system, while Fig. 7 shows a schematic representation of the circuitry. The Energy Management System (EMS) incorporated the Smartgen Reverse Power Protection Relay HPD300, which was connected both to the generator line and the inverters' contactors. When the load power from the inverter decreased to 110 kW (approximately 25% of the generator's nominal power), the EMS initiated the shutdown of inverter G-A. If the load power remains below 25%, the EMS proceeds to deactivate the second inverter (G-B). To assess energy generation and current flow, a thorough examination was conducted using a Fluke energy analyzer of type 434, as illustrated in Fig. 8. Additionally, the inverter efficiency was tested across various input powers. The Energy Management System (EMS) incorporated the Smartgen Reverse Power Protection Relay HPD300, which connected both the generator line and the inverters' contactors. When the load power from the inverter decreased to 110 kW (approximately 25% of the generator's nominal power), the EMS triggered the deactivation of inverter G-A. When the load power persisted below 25%, the EMS subsequently initiated the shutdown of the second inverter (G-B). An indepth analysis of energy generation and current flow was conducted using a Fluke energy analyzer type 434, as depicted in Fig. 8. Furthermore, the efficiency of the inverter was assessed under various input power conditions.

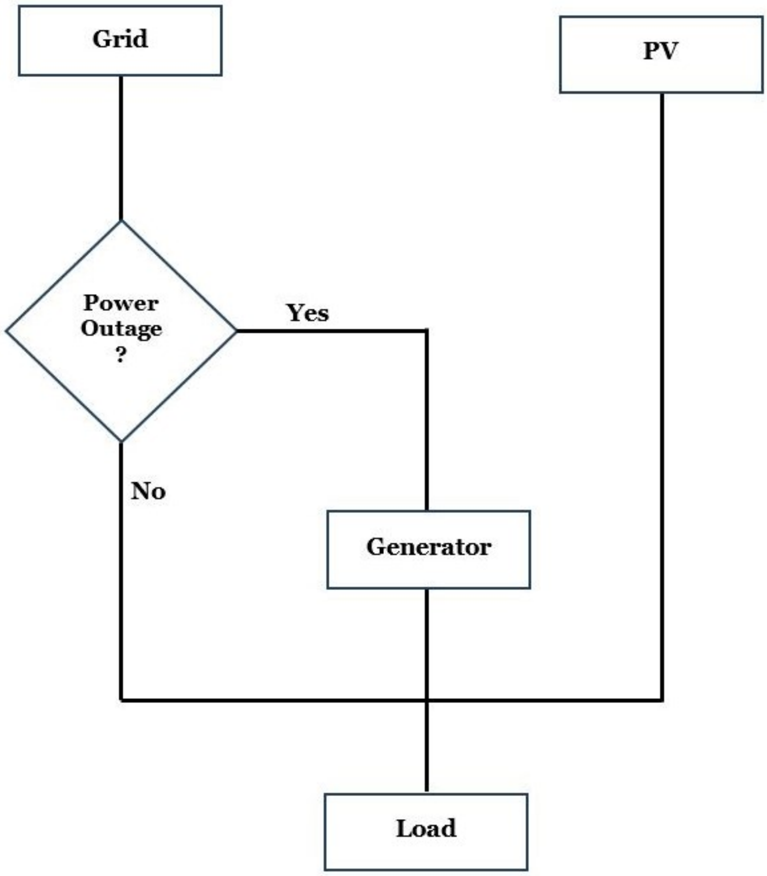

Fig. 6 Flowchart of the Hybrid System.

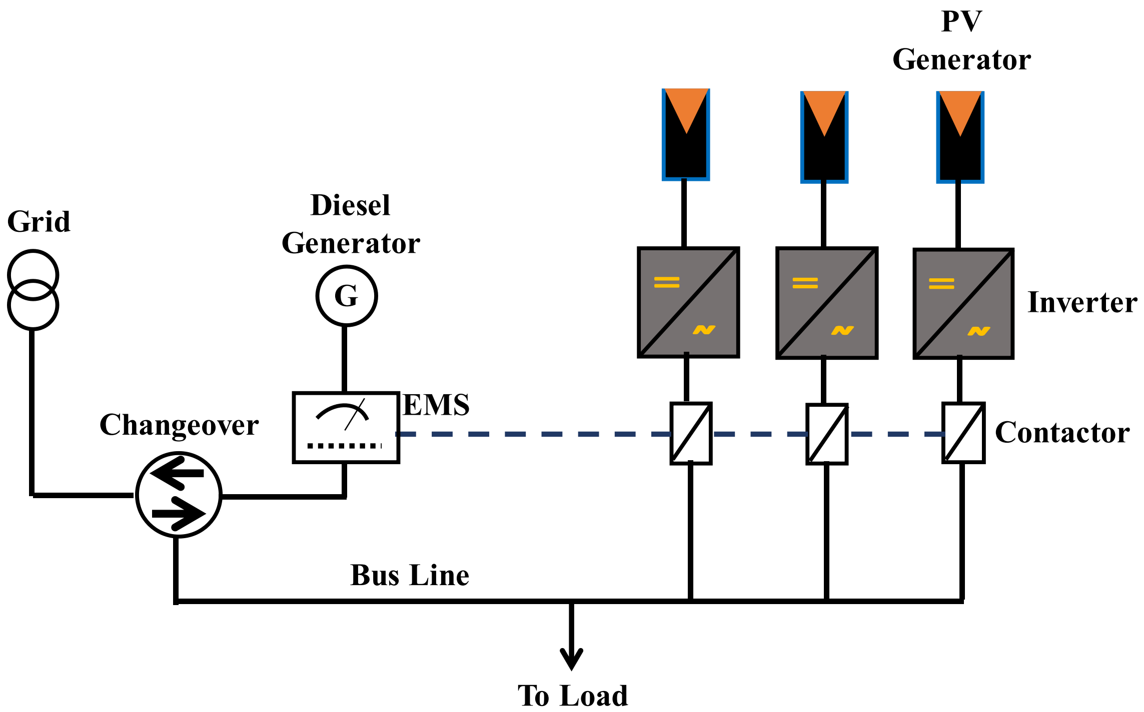

Fig. 7 A Scheme of the PV-Generator Hybrid System.

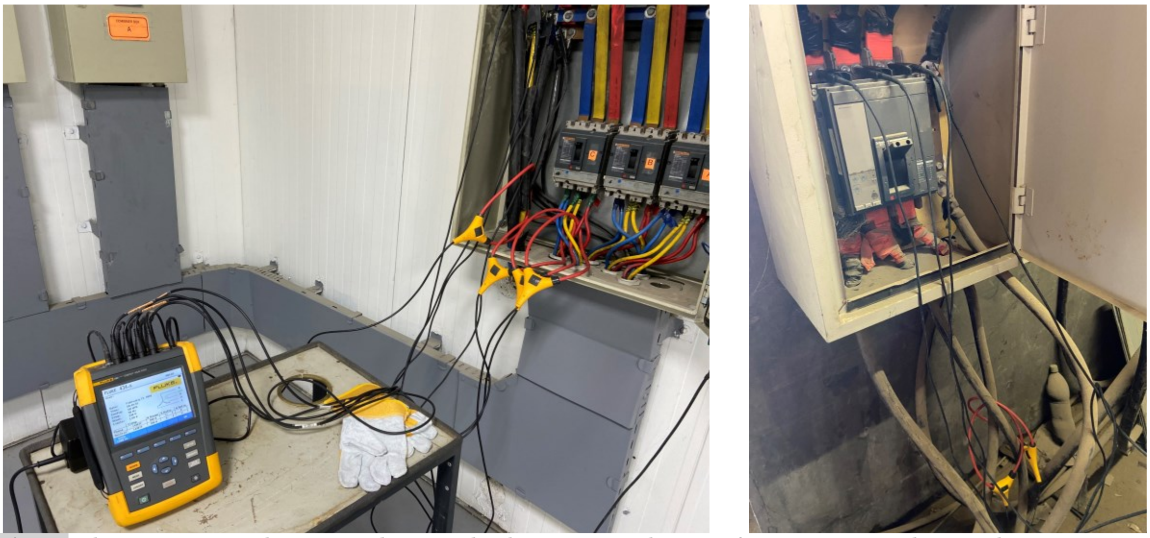

Fig. 8 The Energy Analyzer Used to Study the Energy Flow: Left (Inverters Side), Right (Generator Side).

3.RESULTS AND DISCUSSION

The on-grid PV system presents an ideal solution for governmental institutes, given that these institutions typically operate during daylight hours and commonly cease activities around 2:00 PM, with nocturnal work being infrequent. Additionally, institutional buildings often house substantial power demands, making batteries less practical. Since grid shutdown is expected and occurs daily, a reliable backup system is necessary. Consequently, a PV generator hybrid system emerges as a suitable choice for such structures. The real output power of the on-grid PV system in a REERC building varies depending on the weather conditions. The best performance is achieved between March and April when weather conditions are usually close to STC. The PV power in this period of year reaches around 90kW at noon (out of the nominal 135kW power) with a performance ratio (90/135 = 0.67). The performance ratio is influenced by several factors, such as ambient temperature and ohmic loss [20]. Temperature dramatically reduces the output power of a PV system. Figure 9 exhibits the PV output power on March 9, 2020, as shown on the SMA portal platform. The performance ratio (PR) was low and even dropped to 45% in July and August when ambient temperature reached 50°C. This low PR is due to aging degradation (the system was installed and commissioned in 2014, resulting in at least a 1% drop per year) and also due to some other technical installation issues caused by partial shading of the maintenance bridge frames, which were investigated in Ref. [21]. Another reason is the PV modules' tilt angle, which was 45° instead of the optimal tilt angle for Baghdad city, i.e., 30°.

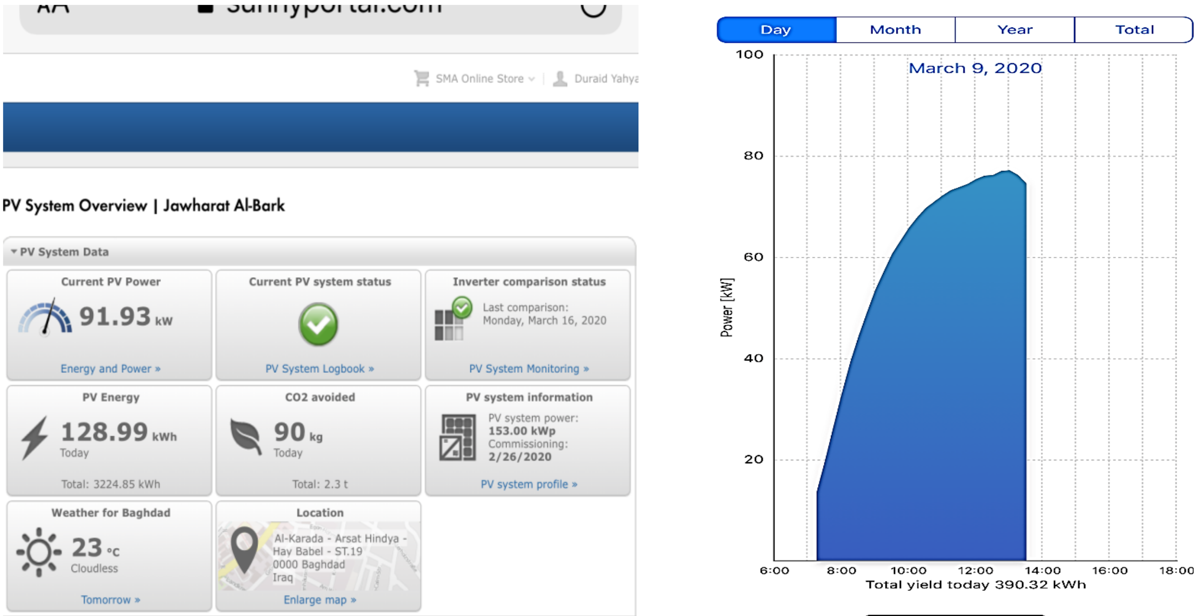

Fig. 9 PV System Real Output Power, as Shown on the SMA Display.

Table 2 illustrates the system's output power and current across different daytime hours. As expected, the PV output power corresponded to the irradiance levels, with the highest power output recorded at 11:00 AM. This outcome is a consequence of the deliberate orientation of the PV modules at 23° East-south, which causes the peak generation to occur slightly before noon. This specific orientation was selected with careful consideration to ensure that the peak hour aligns with the busiest time at the REERC building. The REERC building exhibits varying current consumption depending on the time of day and the season. Typically, the building consumes an amount ranging from 200 A in November to 400 A in August. Referring back to the earlier table, the PV system can supply approximately 50% of the consumed power in August and 100% of the consumed power in November. The data presented in Table 3 was collected on November 18, 2021:

Table 2 PV System Performance and Inverter Output Current.

Time (AM/PM)	Irradiance (W/m²)	Panel Temperature (°C)	PV Input Power (kW)	Inverter Single Phase Current (A)	3-Phase Total Current (A)
8:00	502	29.3	43.6	67.90623	203.7187
9:00	806	44	62.2	96.8754	290.6262
10:00	937	44.9	70.12	109.2107	327.6321
11:00	988	52.2	76.04	118.431	355.293
12:00	984	52.4	75.55	117.6678	353.0034
01:00	924	56.2	74.25	115.6431	346.9293

Table 3 Data Collected on November 18, 2021 from the PV System.

Inspection Date	18-11-2021
Inspection Time	11:00 AM
Weather Conditions	Partially Cloudy
Irradiance	500 W/m²
PV Power	68.11 kW
Produced Current by PV	269.6 A
Consumed Current by REERC Loads	199.4 A
Injected to Grid Current	70.2 A
Total Energy Produced in 6 working hours	339.92 kW.h
Saved Money	41000 Iraqi Dinar (Electricity Tariff is 120 ID)
Avoided CO_2	238 kg

As previously discussed, the PV system is functioning properly, reducing electricity bills and CO2 emissions. However, with regular power shutdowns or random power failures, a generator is essential to keep the research center running. It can be used as a microgrid with the PV system, allowing the generator to operate at low power, which consumes less gas and emits less CO_2, on average. Since there is always a chance that the PV system can inject excess power into the generator, the EMS is crucial to protect the generator from any damage. Figure 10 shows the extracted power from the generator with and without a PV system. The plots were reproduced using OriginLab 9.0 software. The generator without PV, shown in Fig. 9 (a), generates an output power of nearly 100 to 110 kW. The sudden rise steps are due to the consecutive operations of the building loads. Figure 9 (b) shows the generator with inverter A. The output power dropped after synchronizing from 100 kW to around 70 kW, then dropped to 40 kW after synchronizing inverter B (Fig. 9 (c)), and finally dropped to 25 kW after the three inverters synchronized (Fig. 9 (d)), representing almost a zero load operation for the generator. With EMS in service, two inverters (B and C) will be turned off to maintain an operational load of at least 25% of the generator's nominal power. Since the measurements were conducted in February (when the building load was at its minimum), two PV generators were turned off. In summer, with a peak load, the three PV generators can work together with the generator.

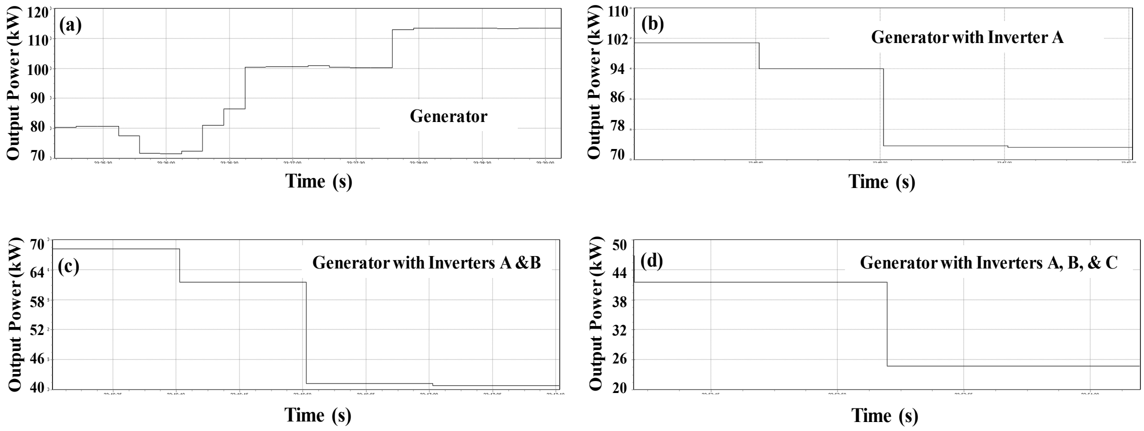

Fig. 10 Generated Power from the Generator in the PV-Generator Hybrid System.

The fuel consumption of a diesel generator is given by [22]:

$$F_d = (a.T_d + b.P_d) \quad (1)$$

where Fd, Td, Pd, a, and b denote the diesel generator fuel consumption rate (l/h), the diesel generator capacity (kW), the diesel generator output (kW), the fuel intercept coefficient (l/kWh), and the fuel slope (l/kWh), respectively. For a given generator, increasing power output (Pd) means increasing fuel consumption (Fd). An inclusion PV system with a diesel generator will result in a decrease in Pd and, consequently, a decrease in Fd, as shown in Eq. (1). However, with excessive PV penetration, the generator may operate at a low load, thereby decreasing its efficiency. The generator efficiency is given by the following equation [22]:

$$\eta = \frac{3600 \times P_d}{P_f \times (a \times T_d + b \times P_d) \times LHV_f} \quad (2)$$

where η, P_f, and LHV_f are the generator electrical efficiency (%), the fuel density (kg/m³), and the lower heating value of fuel, respectively. At low P_d, the generator efficiency decreases, as shown in Eq. (2). Moreover, the generator operating at low load may be damaged, as discussed earlier. Generally, a well-maintained diesel generator operating at its rated power can generate 4 kWh per liter of fuel, decreasing to 2 kWh/l if the generator is operating at a low load. To avoid this in this work, the EMS will reduce the PV penetration by disconnecting one or more inverters. Table 4 presents the gas savings, monetary savings, and avoided CO_2 emissions associated with the PV-generator hybrid system. As depicted in the table, a significant effect is observed with a 69% PV energy share. Approximately, the gas savings were 24 l/h, corresponding to a monetary saving of 8,500 ID/h, since the electricity tariff was 120 ID per kWh. Considering the scenario of diesel operation for four hours daily, this equates to an annual fuel saving of 12 MID. With a PV system cost of 1.2 MID per kilowatt (kW), a 135 kW PV system, with an initial investment of 162 MID, has the potential to recover its initial budget within 13.5 years solely from fuel savings. The present measurements showed that the used generator generated approximately 3 kWh/l when operating at 25% of its nominal power, thereby avoiding 50 kg/h of CO_2, considering that each 1 kWh emits 0.7 kg of CO_2. Those values can be doubled or increased by a few folds with increasing generation load. More money-saving and CO_2-avoiding measures are expected in the summer.

Table 4 PV-Generator Hybrid System Results for One-Hour Measurements.

Parameter	Without PV	With PV
Inspection Date	7-02-2022	8-02-2022
Inspection Time	11:30 AM to 12:30 PM	11:30 AM to 12:30 PM
Weather Conditions	Sunny	Sunny
Irradiance	832-812 W/m²	817-809 W/m²
Generated Energy by Generator	102 kWh	31 kWh
Shared Energy by PV	Zero	71 kWh (69%)
Rated Power Ratio	25%	8%
Consumed Gas	32 litter/hour	8 litter/hour
Saving Gas	Zero	24 litter/hour
Saving Money	Zero	8500 ID/hour
Avoided CO_2	Zero	50 kg/hour

The inverter efficiency (IE), as specified in the company's datasheet, is 96%. However, it is essential to note that this efficiency applies only when the inverter operates at its rated power of 50 kW. In practical terms, the inverter's performance is compromised throughout the day due to variations in solar radiation, resulting in partial-load operation. Furthermore, the selected inverter for the system was already oversized, with a maximum input PV power of 45 kW. Adding to the complexity, the system experienced degradation after 9 years from installation, alongside the previously discussed low-performance ratio (PR). To assess the inverter efficiency over a day, measurements were conducted, and the outcomes are depicted in Fig. 11. Figure 11 shows that when irradiance was low, e.g., at 8:00 AM with 519 W/m², the IE dropped to 71%, significantly deviating from the manufacturer's reported efficiency. As irradiance increased to 845 W/m² at noon, the IE improved to 83%. This result highlights the impact of using an oversized inverter, resulting in notable efficiency losses. Considering these factors, it is advisable to employ a slightly undersized inverter, allowing for better adaptation to the PR (always less than 100%) and accounting for degradation over time. This behavior can contribute to enhanced performance in the PV-generator hybrid system. Additionally, the three inverters were connected to three PV generators, each equipped with 180 modules. Due to variations in power output among the PV generators, an imbalance was raised among the inverters, leading to a mismatch in their operational load distribution. Consequently, this disparity hampers overall efficiency, resulting in an additional reduction in the system's performance.

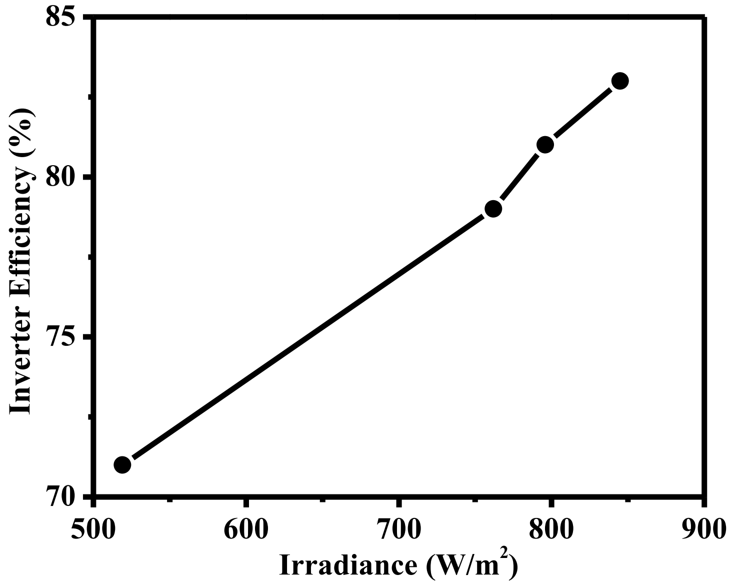

Fig. 11 Inverter Efficiency as a Function of Daytime Irradiance.

4.CONCLUSIONS

In conclusion, the implemented PV-generator hybrid system, which combines an on-grid PV system with a 0.5 MW diesel generator, demonstrated its effectiveness in providing power during grid outages. The system, installed on the Renewable Energy and Environment Research Center building, is designed to maintain a minimum generator load of 25%, ensuring generator safety. This strategy resulted in significant fuel savings, with the generator saving 24 liters of fuel gas per hour, equivalent to a cost saving of 8500 ID/h and a reduction of 50 kg/h of CO2 emissions. Despite the successful outcomes in terms of fuel efficiency and cost savings, the inverter efficiency in the system ranged from 71% to 83%, indicating room for improvement in the overall performance of the hybrid system. Further optimization of the inverter efficiency could enhance the overall effectiveness of the PV-generator hybrid system.

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