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Design of 1.9MW Solar PV System for a Distribution Substation in West Baghdad, Iraq

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ABSTRACT

The increasing demand for reliable and clean energy in Iraq, coupled with the frequent stress on the national grid, has highlighted the need for localized renewable energy (RE) solutions. This study presents the design of a proposed solar photovoltaic (PV) system for a distribution substation located in West Baghdad, aiming to supplement the substation's load with RE, reduce transmission losses, and enhance energy sustainability. The proposed system is tailored to the region's climatic conditions, particularly its high solar irradiance, and is designed with a capacity that ensures compatibility with existing grid infrastructure and operational safety. The methodology involves detailed site assessment, load profiling, and solar potential analysis based on meteorological data. System sizing is carried out using MATLAB/Simulink tool and validated against international standards. Key design elements include panel orientation, inverter selection, mounting structure, and grid integration requirements. Additionally, the study evaluates the economic feasibility and environmental benefits of the proposed installation. Simulation results suggest that the PV system could supply a significant portion of the substation's daytime energy demand, with considerable reductions in carbon emissions and peak load pressures. The findings underscore the viability of distributed solar energy in urban utility networks and provide a reference model for similar projects across Iraq. This initiative aligns with the country's broader goals of enhancing energy security and transitioning toward a more resilient and sustainable power sector.

Keywords: Microgrids, On-grid PV system, Renewable energy, Sustainable power, Solar photovoltaic.

I. INTRODUCTION

The integration and installation of Renewable Energy Sources (RESs) into power systems has increased significantly in recent years. According to International Energy Agency [1], wind power has expanded to about 25% of installed renewable power producing capacity, while solar PV presently accounts for more than 20% of that capacity. About 33% of installed power producing capacity now comes from renewable sources as shown in Fig. 1. Distributed generation (DG) is the term used to refer to RESs since they are connected to power grids at the distribution level.

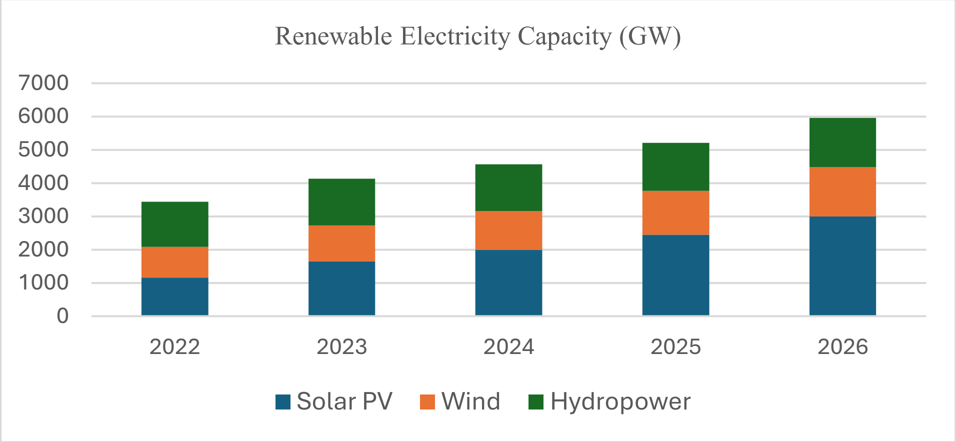

Figure 1: Renewable electricity capacity by technology, 2022-2026 [1].

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The widespread adoption of solar photovoltaic (PV) technology has significantly simplified and accelerated the development of solar farms, requiring minimal effort for deployment. Recent statistics indicate that solar power has emerged as the dominant renewable energy source, with the global installed PV capacity expanding to nearly tenfold its volume compared to a decade ago [1]. This upward trajectory in solar PV deployment is evident in the consistent annual growth illustrated in Fig. 2. Projections suggest that by 2028, global renewable electricity generation will reach approximately 14,400 TWh, marking an increase of nearly 70% from 2022 levels. Several notable milestones are anticipated over the next five years:

1. By 2024, variable renewable sources are expected to exceed hydropower generation.
2. In 2025, renewables will likely surpass coal in electricity generation.
3. Wind energy is projected to overtake nuclear power in 2025.
4. Solar PV is set to exceed nuclear generation in 2026.
5. By 2028, solar PV is forecasted to produce more electricity than wind energy.

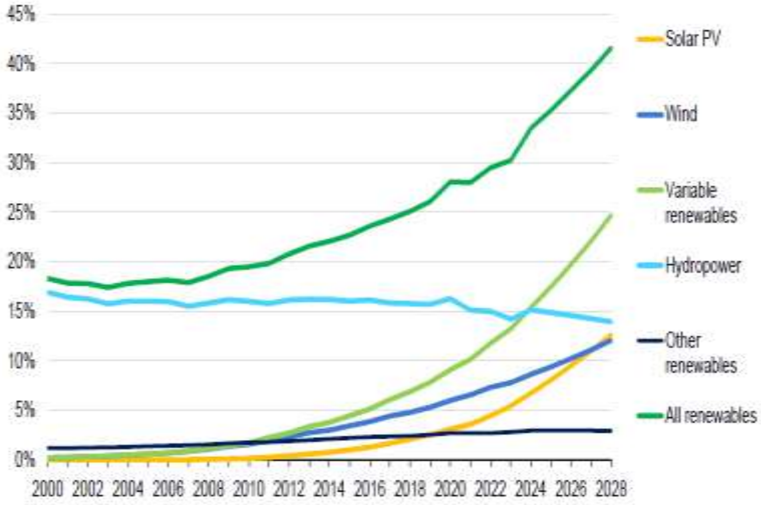

Figure 2: Electricity generation by technology, 2000-2028, [1].

Researchers have explored various filter configurations to mitigate harmonic distortion in electrical systems. Passive power filters, which are generally more cost-effective and require fewer components than their active counterparts, have been employed for this purpose. These fixed passive filters can effectively attenuate harmonics of specific orders when distortion levels are high and relatively predictable. However, their overall performance may be limited under varying operating conditions. Despite the growing concern over harmonic impacts on microgrids (MGs), much of the existing research on inverter control and filter design remains focused on power electronics, often overlooking the comprehensive harmonic behavior of microgrids. Nonetheless, active power filters have garnered considerable attention as a solution to harmonic-related challenges.

I. LITERATURE REVIEW

The advent of on-grid solar PV systems marks a transformative era in the realm of renewable energy, offering a sustainable and increasingly cost-effective solution to the world's growing energy demands. These systems, which are connected to the public electricity grid, harness solar energy to generate electricity, thereby contributing to the diversification of energy sources and the reduction of greenhouse gas emissions. The

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integration of solar PV with the existing grid infrastructure is not without its challenges, including the need for adaptive load-frequency control to manage the intermittent nature of solar power and maintain grid stability [2]. Moreover, the technical complexities such as islanding conditions, power quality, and grid monitoring necessitate advanced detection and control techniques to ensure safety and efficiency [3]. Interestingly, the efficiency of on-grid solar PV systems is influenced by various factors, including geographic location, system design, and the angle of solar panel installation, which can significantly affect the energy output and system performance [4]. Innovations in inverter technology, such as the reduced-switch multilevel inverter, have been proposed to enhance the efficiency and scalability of these systems [5]. The global shift towards renewable energy sources, with solar PV at the forefront, is not only an environmental imperative but also an economic opportunity, as evidenced by the financial viability of large-scale solar PV installations across diverse locations [6]. In summary, on-grid solar PV systems represent a critical component of the global transition to a more sustainable energy future. They offer a promising avenue for meeting energy needs while mitigating environmental impacts. The continuous evolution of technology, system design, and grid integration strategies underscores the dynamic nature of this field and its potential to reshape energy production and consumption patterns worldwide [7].

The design of a 1.6 MW on-grid Solar PV System is a multi-process that involves the integration of various components and considerations to ensure efficient operation and energy production. On-grid systems, such as the 95 kWp system at Karunya Institute of Technology and Sciences, are connected to the electricity grid and can offset energy consumption, reduce bills, and contribute to research activities [8]. Similarly, the analysis of a 100 kWp, grid connected two-stage solar PV system in a MATLAB/Simulink environment highlights the importance of understanding grid dynamics and the impact of faults on system components for reliable grid connectivity [9]. Contradictorily, off-grid systems, like those implemented in remote areas of Inner Mongolia and rural regions of Sindh province, Pakistan, demonstrate the potential for electrification independent of the grid, with economic viability and significant CO2 emission reductions [6]. However, the reliability of off-grid systems, as well as the challenges of power quality and fluctuation in both grid-connected and off-grid modes, are critical considerations for the design of a large-scale on-grid system [5]-[14]. In summary, the design of a 1.9MW on-grid Solar PV System must consider the lessons learned from smaller-scale implementations, the dynamics of grid integration, and the potential for energy savings and sustainability. The system should be tailored to the specific environmental conditions and operational scenarios it will face, ensuring both economic viability and reliability [15]-[18].

II. PV SYSTEM DESIGN

3.1 PV array

The determination of the number of photovoltaic (PV) modules connected in series per string involves several key steps:

A. The maximum allowable direct current (DC) input voltage of the solar inverter is established.

B. Based on this limit, the maximum number of modules per string is defined, ensuring the design remains functional under the coldest daytime temperatures at the installation site.

C. The operational voltage range, considering the highest and lowest ambient temperatures, is then computed using appropriate temperature-voltage relationships.

To model the electrical behavior of solar cells, both single-diode and double-diode equivalent circuit models are commonly used. Among these, the single-diode model is widely adopted due to its balance between simplicity and accuracy. Figure 3 illustrates the single-diode equivalent circuit, incorporating both series and shunt resistances to represent internal losses [19]–[20].

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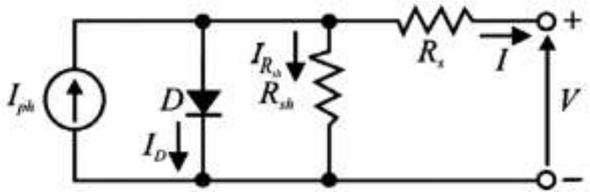

Figure 3: Equivalent circuit of the single-diode solar cell

For a single-diode equivalent circuit, the relationship between the delivered current (I) and the delivered voltage (V) is as follows.:

$$I = I_{ph} - I_D - I_{R_{sh}} \tag{1}$$

$$I = I_{ph} - I_0\{exp[q(V + I.Rs)/(AKT] - 1\} - (V + I.Rs / R_{sh}) \tag{2}$$

The number of PV modules per string is determined using the following considerations:

- The maximum allowable DC input voltage of the solar inverter is identified.
- The system is designed based on the lowest anticipated daytime temperatures at the selected site, allowing for the maximum number of modules per string.
- A temperature-voltage relationship is applied to calculate the range of operating voltages corresponding to the highest and lowest ambient temperatures expected at the installation location.

$$V_{(t)} = V_{(25°)} \times (1 + \alpha_{\upsilon} (T_{\mathrm{m}} - T_{\mathrm{STC}})) \tag{3}$$

-

Where:

$V_{(t)}$: Module output voltage at any temperature.

α_v: Temperature Coefficient of Voltage drop.

T_m: Module temperature in °C.

T_{STC}: Temperature at standard test conditions (25˚C).

The maximal number of modules in each string has been computed in the following equations:

$$Maximum\ No.of\ modules/string = \frac{(\mathrm{Vmax})_{inverter}}{V_{oc\ (Tm.min)}} \tag{4}$$

Likewise, the minimum number of modules per string can be found using the following relation:

$$Minimum\ No.of\ modules/string = \frac{(\mathrm{Vmpp})_{inv.min}}{V_{mpp\ (Tm.max)}} \tag{5}$$

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The total number of parallel strings given the required power is determined by the following equation:

$$No.of\ strings\ in\ parallel\ = \frac{(P_{output\ kW})_{inverter}\ /\ \eta_{max}}{(No.of modules/string) \times (P_{max})_{module}} \tag{6}$$

3.2 MPPT Algorithm

The perturb and observe algorithm, is a commonly used optimization technique in MATLAB, especially for Maximum Power Point Tracking (MPPT) in PV systems. Its goal is to maximize the power output of a PV system by adjusting the operating point of the system. This algorithm works as follows:

1. Perturbation (Change): The algorithm introduces a small change to the voltage or current of the PV system.
2. Observation: It observes the resulting change in the power output; if the power increases, the algorithm continues perturbing in the same direction, while if the power decreases, the algorithm reverses the direction of the perturbation.
3. Iteration: These steps are repeated iteratively until the maximum power point is reached and maintained.

3.3 MATLAB Implementation

In MATLAB, the perturb and observe algorithm is used within custom scripts, Simulink models, or blocks in toolboxes like SIMSCAPE. It involves:

- Creating a function or code block that calculates power.
- Comparing the current power output to the previous one.
- Adjusting the operating point based on the comparison result.

The solar PV system configuration consists of series-parallel combinations PV array, MPPT controller, DC to DC converter, DC to AC inverter, point of common coupling (PCC) to the grid. Fig. 4 shows the system configuration.

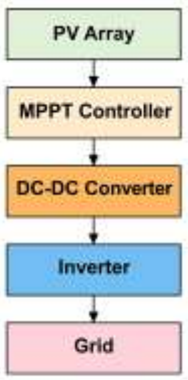

Figure 4: Solar PV system components.

2.4 Steps to Size a Solar PV Array in MATLAB/Simulink

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1. Define system requirements by setting the load demand, location (irradiance, temperature), and design objectives.
2. Select PV module specifications through using rated power, voltage, and temperature coefficients under standard testing conditions.
3. Configure PV array by calculating number of modules in series (based on inverter voltage and lowest temperature) and parallel (to meet power demand).
4. Build and simulate in Simulink by using PV array block with irradiance and temperature inputs and include MPPT, inverter, and load.
5. Add energy storage through the inclusion of battery block to stabilize supply.
6. Run simulation and analyze system performance (energy generation, load matching, efficiency).

Fig. 5 demonstrates these steps in the form of a flowchart.

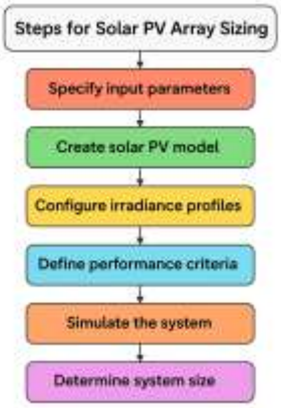

Figure 5: Sizing the solar PV system's flowchart.

III. DESIGN RESULTS

4.1 Selection of PV module

The data for the site geographical parameters are as given in Table 1.

Table 1. Site geographical data.

Geographical Site	Latitude	Longitude	Altitude	Time Zone	PV Field Orientation	Tilt/Azimuth
AL-Mansur, West-Baghdad, Iraq	33.32° N	44.36° E	50 m	UTC +3	Fixed plane, No shadings	33 / 0 °

The overall system design is based on a target power output of 1900 kW. The electricity generated by the PV array is produced at a low-voltage level of 0.4 kV AC. This voltage is then increased to 11 kV using a step-up transformer with a rated capacity of 2.5 MVA, facilitating integration with the 11 kV distribution grid. Table 2

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presents a selection of the latest commercially available PV modules exceeding 500 W in rated capacity. Among these, a 540 Wp module was chosen due to its superior energy output and extended operational lifespan.

Table 2. Brands and specifications of (> 500Wp) solar panels.

Typical Type	520W	530W	540W
Max Power (P_{max})	520	530	540
Max Power voltage (V_{mp})	40.47	40.74	41.04
Max Power current (Imp)	12.85	13.01	13.17
Open circuit voltage (V_{oc})	48.99	49.26	49.53
Short circuit current (I_{sc})	13.53	13.69	13.85
Module Efficiency (%)	20.56	20.96	21.35
Max system voltage	1500V (DC)		
Max Series Fuse Rating	20A		
Temper. Coeff. of Voltage (α_v)	-0.29%		
Dimensions	2230×1134×35 mm		
Weight	28.9 kg		
Front glass	3.2 mm tempered glass		
Output cables	4 mm² symmetrical length1100mm		
Connectors	MC4 Compatible IP68		
Cell type	Mono-Crystalline PERC Half-Cell 9BB 182mm		
Number of cells	144 cells		
Power tolerance	±3%		

4.2 PV inverter ratings

PV inverter is selected according to the system rated power of 2 MW. This inverter consists of two units and has ratings as shown in Table 3.

Table 3. Solar inverter specifications

Max input power	2×1200 kW	Max AC output power	2×1000 kW
DC voltage range, mp	600V-800V	Nominal AC current	2×1445A
Max DC voltage	1100V	Nominal output voltage	400V
Max DC current	2×1710A	Output frequency	50/60Hz
Nominal AC output power	2×1000 kW	Harmonic current distortion	<3%
Power at cos ϕ = 0.95	2×950 kW	Power factor compensation	Yes

4.3 PV array configuration

The configuration of the photovoltaic array was established by determining the maximum and minimum number of modules per string, using Equations (1) through (6), based on Iraq's extreme climatic conditions ranging

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from a minimum ambient temperature of −1°C to a maximum of 60°C. The corresponding open-circuit and maximum power point voltages under these temperatures are calculated as follows:

Open-circuit voltage at −1°C:

$$V_{oc\,(-1^\circ)} = 49.53\,(1 + (-0.0029) \times (-1 - 25)) = 53.26\ V$$

Maximum power point voltage at 60°C:

$$V_{mp\,(+60^\circ)} = 41.04\,(1 + (-0.0029) \times (60 - 25)) = 36.87\ V$$

Based on these values, the maximum number of modules per string is calculated by dividing the inverter's maximum DC input voltage (1100 V) by the open-circuit voltage at −1°C:

$$N_{series,max} = (V_{max})_{\,inverter} / V_{OC\,(-1^\circ)} = 1100/\,53.26 \approx 20$$

Similarly, the minimum number of modules is derived using the minimum operational voltage (600 V) and the voltage at maximum temperature:

$$N_{series,min} = (V_{\mathrm{mp,\,min}})_{\,inverter} / V_{\mathrm{mp}\,(+60^\circ)} = 600/\,36.87 \approx 16$$

A practical value of 18 modules in series per string is selected as a suitable compromise.

To determine the number of parallel strings required to meet the 1.9 MW system capacity using 540 W modules:

$$N_{parallel} = 2 \times 1000\mathrm{kW} \,/\, (18 \times 540) = 208$$

Thus, the PV array consists of 208 parallel strings, each containing 18 series-connected modules. For improved manageability and protection, the system is divided into 16 subarrays, each comprising 13 strings. The total number of modules used is:

$$= 18 \times (13 \times 16) = 3744 \text{ modules.}$$

Figures 6 and 7 present the schematic configuration of the array and the Simulink model of the 1.9 MW on-grid solar PV system, respectively.

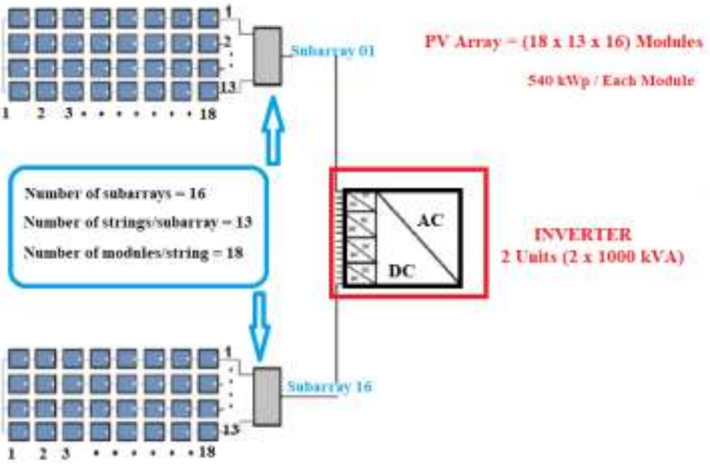

Figure 6: PV array and system layout.

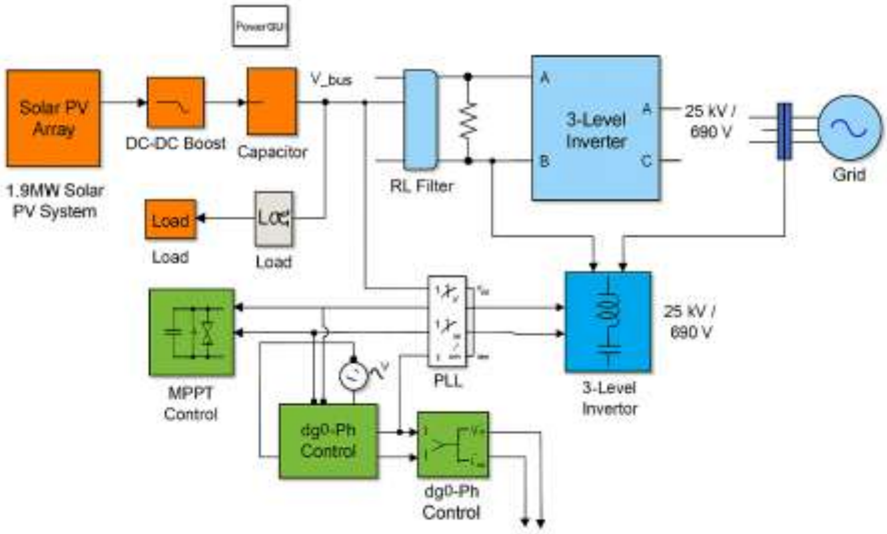

Figure 7: MATLAB/Simulink model for the 1.9MW solar PV system layout.

4.4 Results of system layout

The benchmarked system layout obtained from MATLAB/Simulink software is given in Table 4.

Table 4. Layout of solar PV system.

PV panels	
Manufacturer	SunPower
Panel rated power	540 W_p
Number of modules	3744
Rated (STC)*	2000 kW_p
Strings of series modules	18
Parallel strings	208
Power of maximum power point at 50°C	1900 kW_p
Voltage of maximum power point at 50°C	41 V
Current of maximum power point at 50°C	3420 A
Solar Inverters	
Manufacturer	ABB
Type	Centralized
Unit rated power	950 kW AC
Number of units	2
Operating voltage	600V-800V
Rated power	1.9 MW AC

(*) STC refers to Standard Test Conditions which include:
-Irradiance: 1000 W/m² (solar power per square meter).
-Cell temperature: 25°C (not ambient, but the temperature of the solar cell).
-Air Mass: 1.5 (represents the path length of sunlight through the atmosphere).

The layout obtained from applying the design equation uses state-of-the-art technological components and hence gives better system outcomes and configuration.

IV. CONCLUSIONS

This study presented the design of a 1.9 MW grid-connected solar photovoltaic system intended to supply a distribution substation in West Baghdad. Using MATLAB/Simulink simulation tools, a benchmark system layout was developed to ensure technical feasibility and performance optimization under the region's climatic conditions. The system comprises 3,744 SunPower panels, each rated at 540 Wp under standard test conditions, resulting in a total installed DC capacity of 2,000 kWp. The design employs 18 modules in series per string and

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208 parallel strings, configured to operate efficiently at a maximum power point of 1,900 kWp under elevated cell temperatures (50°C). The DC system interfaces with two ABB centralized inverters, each rated at 950 kW, ensuring a combined AC capacity of 1.9 MW, with a voltage operating range of 600–800 V. The system's configuration reflects a well-optimized layout, balancing electrical output with temperature derating and site-specific conditions. The selection of high-efficiency components and centralized inverter topology contributes to reduced system complexity and increased reliability. These outcomes confirm the viability of integrating a utility-scale solar PV system within Baghdad’s distribution network and support the national objective of diversifying the energy mix with sustainable sources. Future work may explore performance under dynamic load scenarios and grid interaction, as well as economic analysis including levelized cost of energy (LCOE) and payback period evaluations.

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