



Mitigating the impact of increased loads on medium-voltage networks using Strategic PV Integration: Bir Al-Ghanam 30 kV as a case study

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Abstract:

Global warming is one of the biggest challenges of the current century, which has led to an increasing demand for electricity every year, causing increased technical challenges on electricity grids, including system stability and increasing transformer loads. This paper the effects of integrating distributed photovoltaic solar power generation (DSP) into medium-voltage networks as technical solution to these problems, and within a simulation of expected load growth for 2029 in the Bir Al-Ghanam 30 kV loop. A simulation-based methodology using ETAP software was applied to analyze load flow, voltage drop, and system stability under different operational scenarios. The results show that integrating the DSP significantly improves voltage regulation, reduces transmission losses, contributes to grid stability, and enhances overall system performance under projected load growth.

Keywords: load growth; Global warning; system stability; ETAP software; load flow; PV system; Voltage droop.

Introduction

The demand for electricity increased by almost double the annual rate in 2024. Among the most important reasons that contributed directly and mainly to this increase were the increased demand for cooling, as well as the increased demand for electricity in the industrial sector, and also the rapid expansion of data centers and artificial intelligence technologies[1]. In line with this growing global demand, the primary challenge facing Libya's electricity sector is the anticipated growth in demand. This growth threatens to exceed the capacity of the existing system, directly impacting the quality of electricity. Peak demand is projected to reach 12,623 MW by 2029, compared to 9,500 MW in 2024 [2]. Libya's geographical location offers a wealth of untapped potential: abundant solar resources. While it ranks among the world's most solar-rich regions, with an average annual solar irradiance of approximately 2,500 to 3,000 kilowatt-hours per square meter (kWh/m²/year) and annual sunshine exceeding 3,500 hours. This makes it ideally suited for large-scale solar energy projects [3]. While traditional solutions to address the growing demand for electricity, such as replacing power transformers, constructing new transmission lines, or building substations, are themselves part of the problem. They contribute to increased greenhouse gas emissions, exacerbating the underlying issue, and typically incur significant economic costs. And these projects often require lengthy implementation periods, posing challenges to sustainability goals. Therefore, integrating solar energy systems into the electricity grid offers a viable and effective alternative model for addressing multiple objectives, including meeting increasing demand, improving voltage regulation, reducing transmission losses, supporting renewable energy targets, and ensuring the overall sustainability of the system. To ensure the successful implementation of this solution, we need a comprehensive technical

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analysis to guarantee system stability, power quality, and operational reliability. In New Zealand, the impact of increased rooftop solar installations on medium voltage networks was studied. The study concluded that it caused a slight increase in voltage, which was higher in urban areas than in rural and agricultural areas [4]. Gabdullin and Azzopardi assessed PV integration in Malta's low-voltage grids using actual smart meter data and Monte Carlo simulations. They identified voltage rise (not feeder capacity) as the primary challenge, occurring earlier in feeders with high total path resistance and longer lengths. While penetration below 20% caused no issues, voltage problems emerged at 20%-50% penetration depending on feeder characteristics and PV allocation scenarios [5]. In a 2022 study by Zamri et al., the technical feasibility of integrating a 50 MW Large-Scale Solar Photovoltaic (LSS-PV) plant into the grid was analyzed. The study utilized PVSyst for simulation and ETAP for conducting power system analysis, assessments, on a standard IEEE 10-bus test system. The findings revealed that while the integration had a minimal impact on the overall network stability, the optimal selection of the

point of common coupling (PCC) was critical to mitigate adverse effects such as voltage deviations. The study concluded that need for reactive power compensation to maintain voltage stability under contingency conditions [6]. Kim and Ibraheem studied the integration of solar energy into distribution networks and found that it has a clear and evident impact on improving voltage and reducing losses. However, they also identified serious challenges related to voltage spikes and fluctuations. Also the need to calculate the maximum penetration level (MPL) to ensure that grid stability is not negatively impacted. They also emphasized the need to use reactive power compensators effective solutions for voltage problem[7]. Zemitte et al. (2023) used MATLAB/Simulink to study the transient stability of a power system with integrated photovoltaic (PV) in a medium voltage network in Southern Algeria. The results indicated that increasing the penetration level of PV system led to an improvement in system stability under various contingencies, such as grid loss and short circuits. This enhancement was evident in the stabilization of voltage, frequency, and the generator's load angle. This highlights PV's role in strengthening grid resilience[8]. Saidi (2020) investigated the impact of high PV penetration on the Tunisian transmission system by using the PSAT toolbox for bifurcation analysis and dynamic simulations. Dynamic simulations showed that PV integration enhances voltage regulation and complies with grid code requirements during faults. The study also determined the maximum PV hosting capacity of the grid to be 2185 MW .However, simulations showed that sudden PV disconnection caused frequency deviation and voltage dips (6%), particularly in southern regions[9]. Saleh et al. (2012) evaluated the performance of a on grid-connected photovoltaic power station in Tripoli, Libya. The study established that the system was reliable and produced more energy than anticipated. The authors concluded that solar grid integration is a promising solution for Libya, with the primary performance challenge being the instability of the electrical grid itself [10]. While previous studies have explored PV integration, few have focused on developing a comprehensive mitigation strategy for a real-world, inductively-loaded agricultural network under significant future load stress. This research paper addresses this gap by presenting a case study of the Al-Ghanim well loop, through system design, load flow analysis, and sensitivity studies, in order to validate a practical, large-scale plan

2- Case Study

The Bir Al-Ghanam 30 kV network serves as the main power supply for the area extending south of Zawiya and west of Al-Aziziya, serving a large region known for its agricultural activity. It is

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primarily supplied by the Bir Al-Ghanam 220 kV substation, which is connected to the Ruwais gas-fired power plant and equipped with two main transformers with a combined nominal capacity of 200 MVA (2 x 100 MVA). A large electrical network branches off from this substation, consisting of 13 overhead lines spanning 254 km and three underground cables totaling 3.6 km, connecting nine 30/11 kV secondary substations. This network includes 17 distribution transformers with capacities ranging from 10 to 20 MVA. The current demand on the ring is approximately 150 MVA, and the ring is characterized by agricultural inductive loads dominating network loads, which poses additional operational challenges. It is worth noting that the Nasser and Bir Huwaisa substations are experiencing the largest voltage drops due to the increased demand for electrical power in them. This makes them a crucial indicator of grid performance and a prime candidate for implementing Distributed Generation (DG) solution

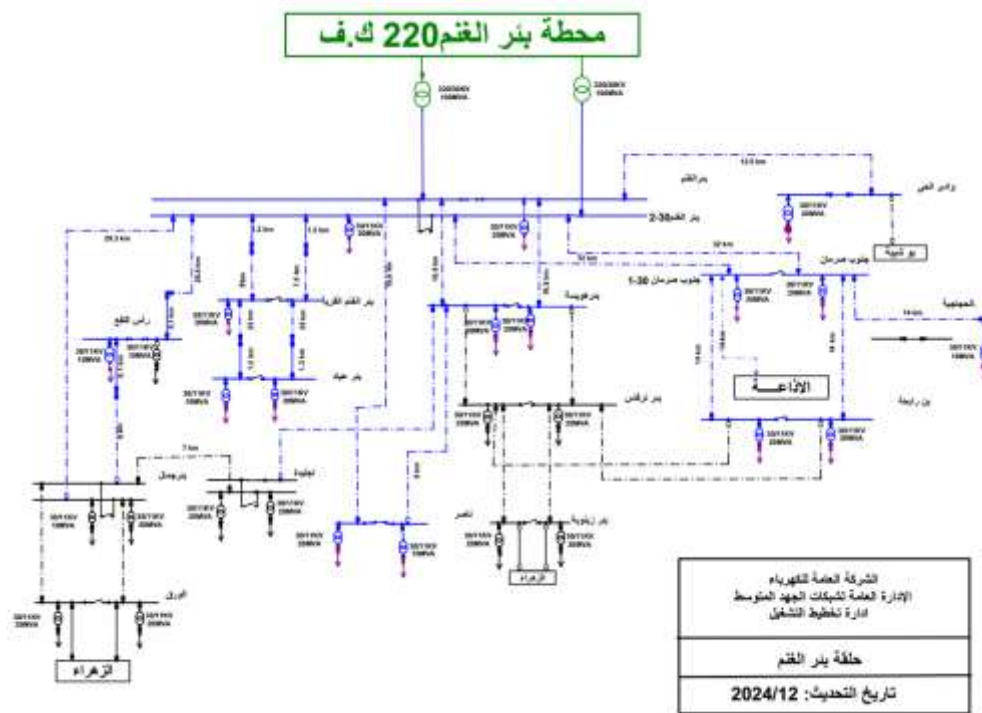


Figure 1: Bir al-Ghanim 30 kV ring.

3. Methodology

3.1. System Description

The Bir al-Ghanam 30 kV substation was chosen for this study because it covers a large agricultural area, meaning it is predominantly subject to inductive loads. This leads to a significant voltage drop, especially at its remote terminals. The problem is exacerbated by increased loads due to anticipated future demand increases [11].

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Complete operational and technical data, including the loop diagram and all technical specifications for the overhead lines, cables, and transformers, were obtained through the Planning and Operations Department of the General Electricity Company of Libya (GECOL).

3.2. Load Modeling and Forecasting

he study was based on the actual loads for 2024 and the projected loads for 2029. Future loads for 2029 were predicted using data from the Planning Department of the General Electricity Company of Libya (GECOL) at an annual rate of 8%. This method was applied to all network points.

3.3. PV Power Plant Design and Sizing

The PVsyst v8.0.15 software was used to design the solar power systems. It was used to model six stations distributed across weak points in the grid. Solar radiation, wind speed, and humidity data for these areas were utilized. The system capacity was approximately 69.37 MW, employing polycrystalline photovoltaic panels (YL255P-29b, Yingli Solar) with a nominal power rating of 255 W peak and an efficiency ranging from 15.2% to 15.6%, chosen for their proven durability in harsh climatic conditions. Sunny Central 2200 (SMA) central inverters were also used in the design, providing a conversion efficiency of 98.8%. The system was optimized to achieve a performance ratio (PR) exceeding 82.35%, taking into account various technical losses.

3.4. Grid Integration and Stability Analysis

A complete grid model was built using ETAP version 19.0.1. While Power flow and stability analyses were performed on this model, employing two main scenarios:

Scenario 1: To understand the system, identify its weaknesses, and establish a reference point, the grid was simulated based on the actual 2024 loads and also with the projected 2029 loads. This was done without integrating solar power systems.

Scenario 2: The system was re-simulated with the 2024 and 2029 loads, but after integrating the solar power plants into the grid.

Finally, the results were compared with the standard operating parameters of the General Electricity Company of Libya (maintaining voltage within $\pm 6\%$ of the nominal value and equipment load below 100%) to evaluate the system's technical feasibility.

4- Results and Discussion

4.1. Base Case Analysis: Operational State of the Network in 2024

Load flow analysis of the Bir Al-Ghanim ring under load conditions in 2024 revealed that the system is experiencing critical periods and significant operational and technical problems. While the total demand on the system was 154.2 MVA with a low lagging power factor of 82.5%. The

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analysis also showed a sharp and dangerous voltage drop at many points in the network, particularly at the network's periphery. A major reason for the low power factor and voltage is the nature of the inductive loads (primarily agricultural loads). A clear voltage drop was observed at the Nasser substation (bus 4) and the Bir Huwaisa substation (bus 45), reaching 88.6% and 89.7% of the nominal voltage value, respectively. These values are significantly lower than the minimum operational voltage value according to the General Electricity Company of Libya's standard specifications (i.e., above 90%) [12]. If this situation persists, it could lead to various damages to the network and to consumers. Either we can also observe that there is overloading at several points in the network. For example, at the Nasser substation, transformer T10 is loaded at 108% of its nominal capacity. This significant increase in transformer load is a warning sign of potential network collapse at any moment due to the risk of transformer failure. Furthermore, this will lead to network failure and a decline in network reliability. In addition, the analysis reveals substantial energy losses, with total active power losses in the network reaching 1.8 MW and reactive power losses reaching 23.8 MVAR. These significant losses represent direct economic losses and are also a major cause of voltage drops in the network, contributing significantly to reduced network efficiency.

From the above, the main problems in the network become clear: critical voltage drops, overloading, and high losses combined, the network to operate under precarious conditions and be susceptible to collapse at any moment. Moreover, it cannot bear additional loads to accommodate anticipated growth unless fundamental and major interventions are implemented. Hence, we find that using the technology of integrating distributed solar power generation stations into the grid will contribute to ending these problems and improving the efficiency of the grid, which will contribute to increasing the reliability and dependability of the grid and improving its overall performance.

4.2. Future Load Scenario (2029) and Performance with PV Integration.

When the network is loaded with the projected loads for 2029, an analysis using ETAP software clearly reveals the extent of the serious problems threatening its very existence. These problems have intensified and reached critical levels. They can be summarized as follows: severe voltage drops, equipment overload, and significant energy losses.

Due to the extensive network branches and high energy demand, voltages have fallen below the minimum standard values for General Electricity Company of Libya at various points the General Electricity Company of Libya, for example Nasser, Bir Hawisa, Ben Rabha, South Surman, and Al-Hajjajiyah substations. Overloading has been the primary cause of the problems, with many transformers operating above their rated capacity. For example, the two main power transformers in the Bir Al-Ghanam 220/30 kV substations, T1 and T2, are loaded at 111.1% and 103.3%, respectively. Furthermore, the distribution transformers in the ring are operating above their nominal capacities. For example, the loads on transformers T10, T11, and T12 reach 145.3%, 103.4%, and 111.6%, respectively. It is obvious that such an operating situation will undoubtedly lead to a rapid collapse of the network and damage to its equipment. The enormous scale of network losses is also clearly evident, particularly in the long transmission lines and power transformers. These losses are estimated at 3.5 MW (active power) and 45.9 MVAR (reactive power). They are concentrated in the Bir al-Ghanam and South Surman areas, resulting in decreased network efficiency and increased operating costs.

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In total, these combined problems are enough to destroy any network unless a comprehensive network recovery plan is implemented. Given the region's vast land area and high solar irradiance this research paper proposes solar power plants as a grid rescue plan, given the region's vast land area and high solar irradiance. The core idea is to inject energy directly into load centers, which will naturally reduce losses in transmission lines and transformers. Furthermore, reducing the energy flow across the grid will alleviate pressure on grid equipment such as transmission lines and transformers, thus providing direct voltage support at low voltage points. Based on grid simulation results, including power plant voltage, loads, and load flow across the grid, the location and size of the solar power plants were selected to ensure stable and safe grid operation. Based on the above, this study proposed injecting 96 MW of solar energy into six main points distributed between 30 kV and 11 kV voltages. As shown in Table No. 1, 40 MW were injected into the South Surman ,Bir Huwaisa and Nasser stations, while in the 11 kV voltage networks, a megawatt line was injected distributed among the Bir Huwaisa, Bin Rabha and Al-Hajjajia substations.

Table 1. Locations and capacities of photovoltaic solar energy injection systems

Sub Station ID	Bus ID	Nominal Voltage (KV)	PV size (MW)
South Sorman	Bus 52	30	8.761
South Sorman	Bus 79	30	8.761
Bir Huwaysa	Bus 74	30	8.761
Bir Huwaysa	Bus 75	30	8.761
Nasser	Bus 77	30	5.257
Al-Hajjajia	Bus 82	11	8.761
Bir Huwaysa	Bus 49	11	8.761
Bir Huwaysa	Bus 50	11	8.761
Nasser	Bus 56	11	8.761
Bin Rabha	Bus 81	11	5.257
Bin Rabha	Bus 84	11	5.257
Bir al-Ghanim	Bus 86	11	5.257
Bir al-Ghanim	Bus 88	11	5.257

Beyond resolving these technical challenges, the integration of PV power plants offers substantial environmental and economic benefits, including the reduction of greenhouse gas emissions and long-term economic feasibility, positioning it as a sustainable solution for the network's future development

We can observe that the network situation after solar energy injection has changed significantly, as there has been a great improvement in network performance and stability. All buses previously experiencing critical under-voltage conditions are now within limits as shown in Table2.

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Table2. Comparing bus voltages before and after PV solar

Sub Station ID	Bus ID	Nominal Voltage (KV)	Case1 before PV solar	Case2 after PV solar
Nasser	Bus 4	11	9.227	9.394
Nasser	Bus 3	11	9.476	9.605
Bir Huwaysa	Bus 45	11	9.384	9.531
Bir Huwaysa	Bus 44	11	9.437	9.580
Bin Rabha	Bus 57	11	9.723	9.841
Bin Rabha	Bus 58	11	9.789	9.925
Bir al-Ghanim	Bus 5	11	9.668	9.791
South Sorman	Bus 20	11	9.828	10.017

The localized generation from PV plants reduced the long-distance power transfer, directly boosting voltage profiles at load centers and alleviating the loading on key transformers to well within their operational limits as shown in Table3.

Table 3 transformer loading before and after PV solar

Sub Station ID	Transformer ID	Rating (MVA)	Loading before PV solar (MVA)	Loading after PV solar(MVA)	Loading before PV solar (%)	Loading after PV solar (%)
Nasser	T10	10	14.53	8.37	145.3%	83.7%
Bir Huwaysa	T12	20	22.33	15.66	111.6%	78.3%
Bir al-Ghanim 220KV	T1 (Main)	100	111.08	68.94	111.1%	68.9%
Bir al-Ghanim 220KV	T2 (Main)	100	103.25	69.01	103.3%	69.0%
Bir Huwaysa	T11	20	20.68	14.14	103.4%	70.7%
Bir al-Ghanim	T8	20	19.5	15.27	97.5%	76.4%

Consequently, system efficiency has markedly improved. Active power losses were reduced from 3.5 MW to 2.29 MW (a 35% reduction), and reactive power losses decreased from 45.9 Mvar to 30.06 Mvar (a 34% reduction). This enhances the network's operational efficiency, reliability, and available load-serving capacity. Furthermore, this strategy yields significant environmental benefits through reduced emissions and promotes the sustainability of the power supply.

After simulating the network under projected loads in 2029, and conducting technical analyses such as load flow, stability, sensitivity, and reliability analysis, it was found that the the most unstable bus 82 (11 kV, Al-Hajjajiyah substation), where the sensitivity factor was found to be 1.00, confirming its high sensitivity to changes in reactive power.

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Finally, based on the network analysis results under the proposed solar energy integration strategy, the network has become stronger, more stable, and more reliable under the projected loads for 2029. It is also recommended to install dynamic reactive power support devices, such as a STATCOM or a switching capacitor bank, at the Al-Hajjajiyah substation to increase the network's resilience to unexpected load increases.

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