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Abstract:
Electrical power networks in Libya are facing increasing operational challenges due to continuous load growth and ageing infrastructure, necessitating systematic planning and redesign. This paper presents the redesign of a 30 kV distribution network in the Bir al-Ghanim area through the integration of advanced photovoltaic (PV) generation technologies. The study incorporates load growth analysis and long-term demand forecasting over a 20-year horizon using engineering simulation methods implemented in ETAP software. The proposed approach evaluates the technical performance of the upgraded network, focusing on its ability to address current operational issues while accommodating future load expansion. The results demonstrate that PV integration significantly enhances energy efficiency, reduces environmental impact, and improves overall network reliability. Moreover, the redesigned grid aligns with international standards and facilitates the adoption of

smart grid concepts. The findings confirm that PV deployment represents not only an effective solution to current efficiency limitations but also a strategic pathway toward a sustainable and resilient energy future in Libya

Keywords: load forecasting; renewable energy; photovoltaic generation; Bir al-Ghanim network; ETAP; load flow.

تحليل نمو الأحمال وتحسين مقطع من شبكة القدرة الكهربائية الليبية بالاعتماد على الطاقة المتجددة باستخدام برنامج ETAP

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الملخص

شبكات الطاقة الكهربائية في ليبيا تواجه تحديات تشغيلية متزايدة بسبب النمو المستمر في الأحمال وتقادم البنية التحتية، مما يستلزم تخطيطاً منهجياً وإعادة تصميم. تعرض هذه الورقة إعادة تصميم شبكة توزيع جهد 30 كيلوفولت في منطقة بئر الغنم من خلال دمج تقنيات التوليد الكهروضوئية (PV)المتقدمة. تتضمن الدراسة تحليل نمو الأحمال والتنبؤ بالطلب على المدى الطويل على مدى أفق زمني يبلغ 20 عاماً باستخدام أساليب المحاكاة الهندسية المطبقة في برنامج ETAP. يُقيّم النهج المقترح الأداء الفني للشبكة المطوّرة، مع التركيز على قدرتها على معالجة المشكلات التشغيلية الحالية مع استيعاب التوسع المستقبلي في الأحمال. تُظهر النتائج أن دمج الطاقة الكهروضوئية يعزز كفاءة الطاقة بشكل كبير، ويقلل من الأثر البيئي، ويحسن من موثوقية الشبكة بشكل عام. علاوة على ذلك، تتوافق الشبكة المعاد تصميمها مع المعايير الدولية وتُيسّر اعتماد مفاهيم الشبكات الذكية. تؤكد النتائج أن نشر الطاقة الكهروضوئية لا يمثل فقط حلاً فعالاً للقيود الحالية المتعلقة بالكفاءة، بل أيضاً مساراً استراتيجياً نحو مستقبل طاقة مستدام ومرن في ليبيا.

الكلمات المفتاحية: التنبؤ بالأحمال؛ الطاقة المتجددة؛ التوليد الكهروضوئي؛ شبكة بئر الغنم؛ برنامج ETAP؛ تدفق القدرة.

1. Introduction

Libya's electrical distribution system has experienced a sustained and substantial increase in electricity demand during the past two decades. An annual growth rate of approximately 8% has been reported for local planning studies, a value that is significantly higher than the global average. Such rapid growth creates a direct requirement for new distribution facilities and for reinforcement of existing networks so that reliability and operating efficiency can be maintained under future demand conditions [1].

Urban expansion, changing land-use patterns, and the geographic spread of new loads make systematic and economically viable network planning essential [2]. Load forecasting is central to this process because it estimates future power and energy requirements and enables utilities to coordinate supply, investment, maintenance, and long-term network development [3].

Forecasting methods are commonly grouped into short-, medium-, and long-term categories according to their planning purpose [4]. The available techniques range from regression and Autoregressive Integrated Moving Average (ARIMA) models to artificial neural networks, support-vector machines, and deep-learning methods [5], [6]. Intelligent methods are particularly useful where the demand pattern is nonlinear and is influenced by rapid urban or socioeconomic change.

For Libya and comparable developing systems, forecasting can be improved by incorporating climatic, demographic, and economic variables. Hybrid models that combine time-series information with weather and regional indicators have shown strong capability to represent seasonal and spatial demand variation [7]. Forecasting alone, however, is not sufficient: load-flow analysis is also required to quantify bus voltages, branch loading, power losses, and the ability of the network to supply the forecast demand. Specialized distribution-system algorithms and simulation platforms are often preferred because large radial and weakly meshed networks can present convergence and modeling difficulties for classical transmission-oriented formulations [8].

The increasing cost of fossil-fuel generation and growing environmental concerns have also strengthened the case for distributed renewable generation. Properly located PV generation can reduce feeder losses, improve the voltage profile, relieve congestion, and enhance reliability by supplying part of the demand close to the point of consumption [9]. In this study, ETAP is used to examine the Bir al-Ghanim 30 kV ring network over the 2024-2034 planning horizon, assuming 8% annual demand growth. The analysis identifies present and future constraints and evaluates the effect of PV integration on voltage, line loading, losses, and network reliability.

2. Distribution System

The boundary between transmission and distribution becomes less distinct when sub-transmission networks are considered. A distribution system generally comprises the facilities between the sub-transmission level and the final consumer, including distribution substations, primary feeders, distribution transformers, secondary feeders, and service connections. Sub-transmission networks form the intermediate stage between bulk transmission and local distribution.

Voltage level is normally used to distinguish transmission, sub-transmission, and distribution functions because it directly influences conductor selection, transformer design, insulation coordination, protection, switching, and metering. In the Libyan system, the 30 kV network is commonly treated as a sub-transmission or medium-voltage level, while lower voltages supply the distribution and end-user stages.

Studying the 30 kV level is important because it reveals where long feeders, overloaded transformers, or weak voltage support may limit future operation. It also provides the appropriate level at which distributed PV can be assessed as an alternative or complementary measure to conventional reinforcement. Figure 1 shows the generic

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arrangement adopted for the 30 kV sub-transmission discussion in this paper.

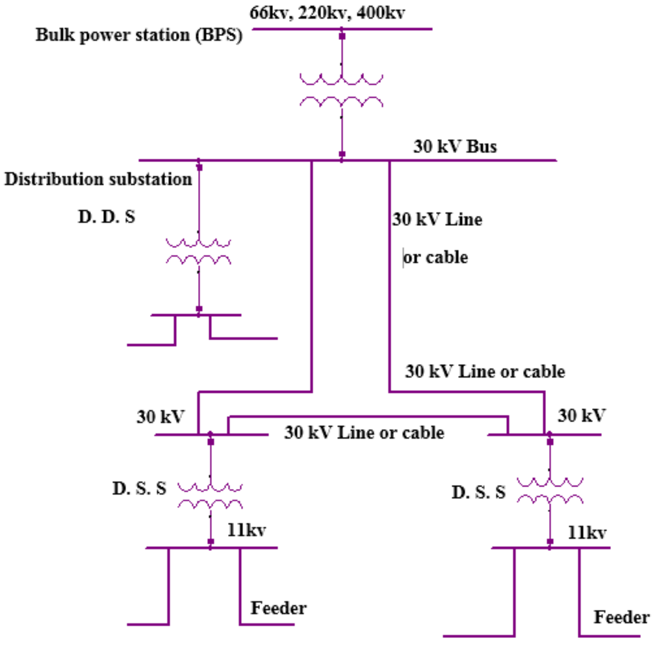

Figure 1. Generic arrangement of a 30 kV sub-transmission network

The subsequent analysis considers the transmission and distribution chain as an integrated planning problem, since constraints at the 30 kV level can propagate to downstream substations and consumers.

3. Load Forecasting for Power-System Planning

Load forecasting estimates future electrical demand over horizons that range from minutes to decades. It supports generation scheduling, energy purchasing, switching, maintenance, contract evaluation, and infrastructure investment. Long-term forecasting is particularly important because it provides the quantitative basis for power-plant development, transformer replacement, line reinforcement, and distribution-network expansion [10].

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3.1 Categories of Load Forecasting Techniques

The principal forecasting horizons are very short term, short term, medium term, and long term. Very-short- and short-term forecasts support real-time balancing and daily operation. Medium-term forecasts support maintenance and fuel planning, whereas long-term forecasts guide strategic decisions such as the construction of generation, transmission, and distribution assets.

3.2 Factors Affecting Long-Term Demand

Long-term electricity demand is influenced by population, living standards, economic activity, fuel supply and price, electricity tariffs, weather, government policy, regional development, and random disturbances. The interaction of these factors is summarized in Figure 2.

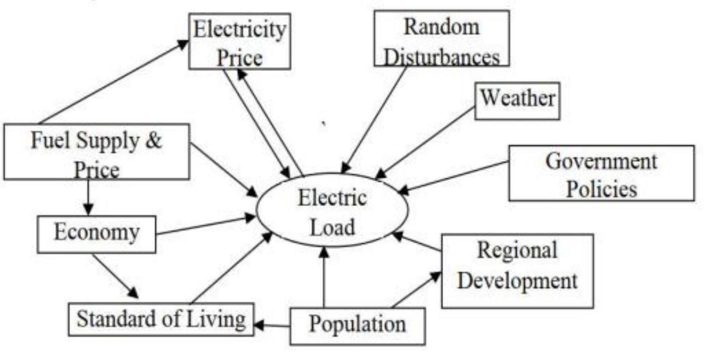

Figure 2. Principal variables that influence long-term electricity demand.

When detailed explanatory variables are unavailable, a constant compound-growth model provides a transparent planning approximation. The projected demand after n years is calculated from [11]:

$$P_n = P_0(1 + g)^n \quad (1)$$

Where:

P_n is the forecast load after n years, P_0 is the base-year load, g is the annual growth rate expressed in per unit, and n is the number of elapsed years.

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The Bir al-Ghanim cases use g = 0.08.

Although this expression is simple, it provides a reproducible reference trajectory against which more advanced statistical or artificial-intelligence models can later be compared.

4. Power-Flow Analysis

Power-flow analysis determines the steady-state operating condition of an electrical network. It calculates voltage magnitudes and angles, active and reactive power flows, equipment loading, and system losses from a single-line network representation and its electrical parameters. These results are essential for verifying voltage quality, identifying overloaded components, and evaluating expansion alternatives [12].

The buses in a conventional load-flow model are classified as follows:

- PQ or load bus: active and reactive demand are specified, while voltage magnitude and angle are calculated.
- PV or generator bus: active power and voltage magnitude are specified, while reactive power and angle are calculated.
- Slack or swing bus: voltage magnitude and angle are specified, while active and reactive power are adjusted to balance the network and its losses.

Load forecasting and power-flow analysis therefore form a coupled planning process: forecasting defines the demand scenario, and the power-flow solution determines whether the network can supply that demand within technical limits.

5. Renewable-Energy Integration

Renewable generation is increasingly integrated into distribution networks to reduce fuel consumption, greenhouse-gas emissions, and dependence on centralized supply. Solar generation is commonly deployed as concentrating solar power (CSP) or photovoltaic generation. CSP converts solar heat into mechanical and then electrical energy and can be combined with thermal storage to improve dispatchability [13]. PV systems convert solar radiation

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directly into DC electricity through the photovoltaic effect illustrated in Figure 3.

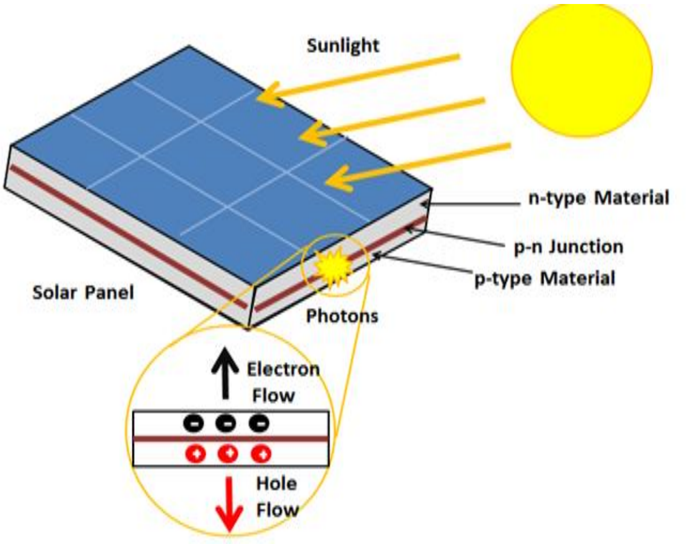

Figure 3. Simplified representation of the photovoltaic effect

PV technology is modular and can be installed as a utility-scale plant or as distributed generation close to load centers. Grid-connected inverters convert DC output to AC and can provide voltage or reactive-power support when their controls and ratings permit. Maximum-power-point tracking (MPPT) continuously adjusts the array operating point so that the available solar energy is extracted under changing irradiance and temperature.

5.1 PV-Farm Configuration

The modeled PV farm comprises multiple arrays connected to DC converters and grid-tied inverters. The inverter output is coupled to the 30 kV network through a step-up transformer. Figure 4 shows the functional arrangement used to represent the PV system and its connection to the network.

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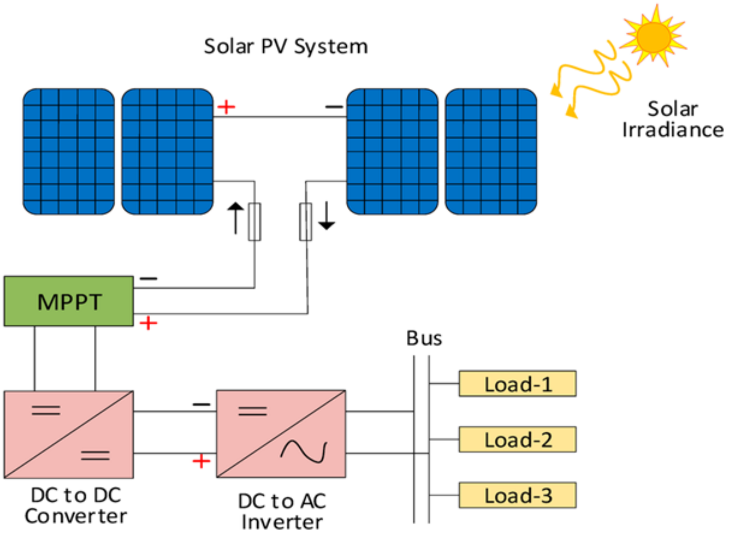

Figure4. Functional block diagram of a grid-connected PV farm

5.2 PV-Module Data

The ETAP model uses a mono- crystalline Suniva ART245-60-3-1 module with 60 cells. The principal electrical and thermal parameters entered in the model are:

- Rated output power: 239.7 W.
- Voltage and current at maximum power: 30.65 V and 7.82 A.
- Open-circuit voltage and short-circuit current: 37.08 V and 8.33 A.
- Module efficiency: 14.9%; fill factor: 77.6%.
- Nominal operating cell temperature: 45 °C.
- Short-circuit-current temperature coefficient: 0.036; open-circuit-voltage temperature coefficient: -0.332; irradiance coefficient of open-circuit voltage: 0.045, as entered in the source ETAP model.

The P-V and I-V curves in Figure 5 describe the response of the module to changes in irradiance and temperature. These characteristics are required for sizing the array, selecting the inverter, and estimating output under the operating conditions represented in ETAP.

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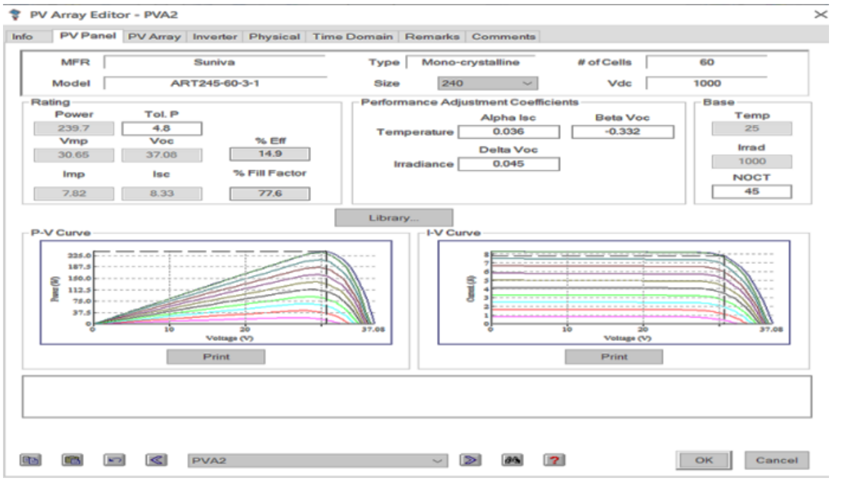

Figure 5. PV-array data and simulated P-V and I-V characteristics in ETAP

6. Case-Study Analysis

The Bir al-Ghanim 30 kV ring network is used as the case study. The 2024 operating model is first solved with the reported peak loads, after which an 8% annual compound growth rate is applied to establish the 2029 and 2034 planning conditions. Each year is examined before and after the introduction of PV at buses or feeders with voltage or loading violations.

6.1 Analysis Procedure

- Perform a load-flow study for the August 2024 peak-load condition and identify overloaded lines, overloaded transformers, and buses outside the permitted voltage range.
- Apply the compound-growth relation to project the demand to 2029 and 2034.
- Assess short- and long-term network performance and identify the reinforcements required in each planning state.
- Connect PV generation at critical buses and feeders to supply part of the local demand and improve voltage support.
- Compare the pre- and post-improvement operating states, including voltage violations, branch loading, and technical losses.

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6.2 Modeling Assumptions and Limits

- The base peak loads are taken from the August 2024 GECOL operating data represented in the ETAP model.
- The 30/11 kV transformers are evaluated at their rated MVA capability.
- The normal bus-voltage range is 0.95-1.05 p.u.; the contingency range is 0.90-1.10 p.u.
- The normal branch-loading limit is 100%, and the contingency limit is 120%.
- The growth calculation assumes a uniform proportional increase in demand across the Bir al-Ghanim area.

Figure 6 presents the ETAP single-line model and the 2024 network data used as the starting point for the study.

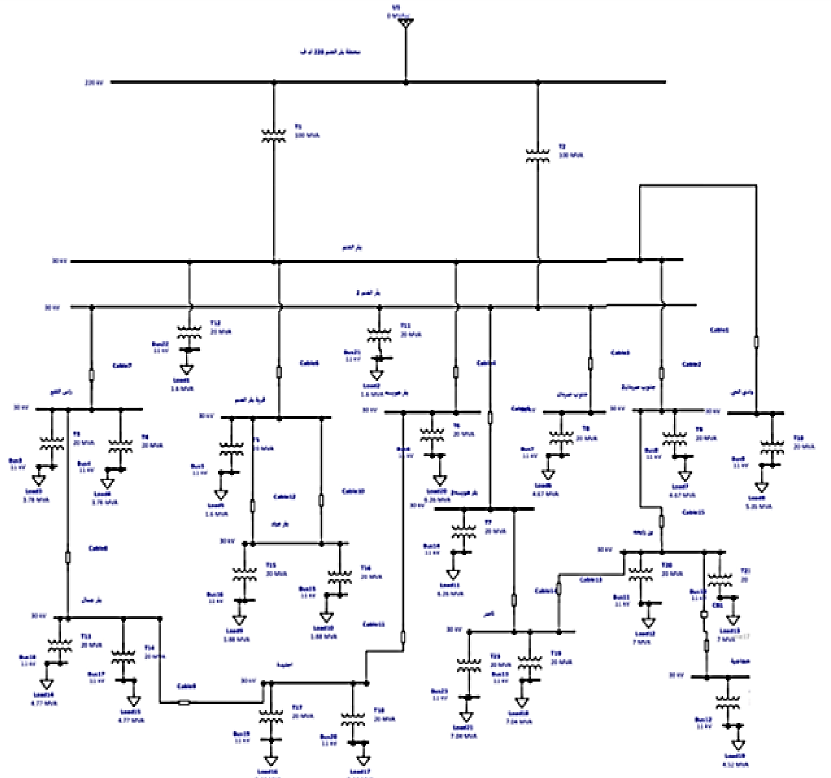

Figure 6. Bir al-Ghanim 30 kV ring network and the 2024 base-case data

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6.3 Case I: 2024 Before Improvement

The base-case solution represents the network under its actual 2024 peak operating condition. The ETAP alert indications identify locations with excessive loading or unacceptable voltage. These violations establish the technical need for corrective action and provide the comparison basis for the first PV-integration case in Figure 7.

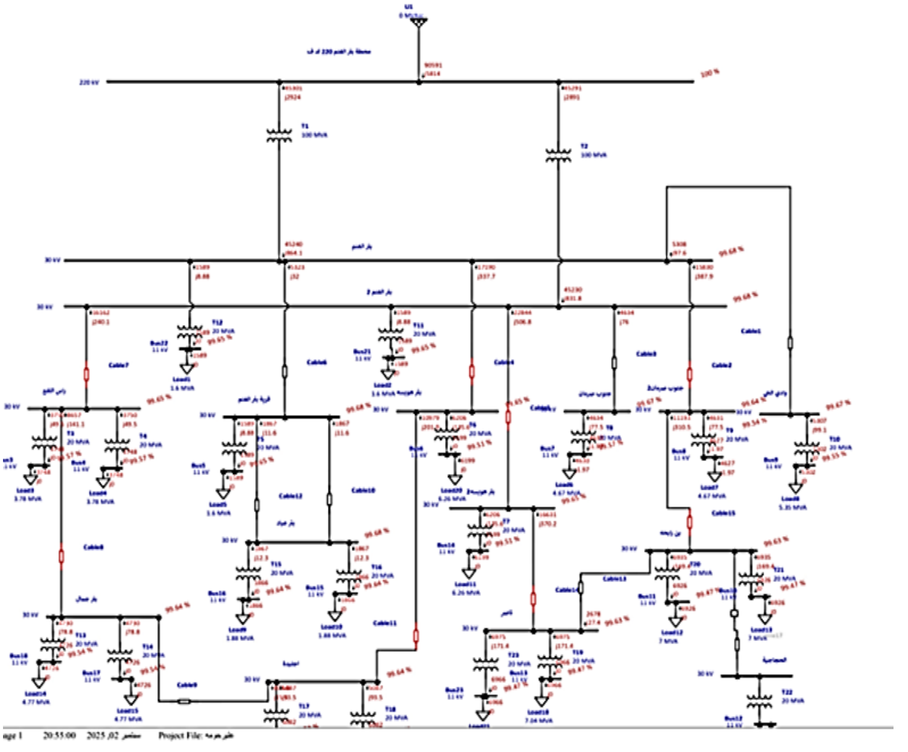

Figure 7. Bir al-Ghanim network in 2024 before optimization

6.4 Case II: 2024 After PV Integration

PV generation is introduced at selected critical locations in the 2024 model. The local generation reduces the net power transferred through the stressed branches and improves the receiving-end voltage. The post-improvement state shown in Figure 8 exhibits fewer alerts and a more stable voltage profile, indicating improved operating reliability.

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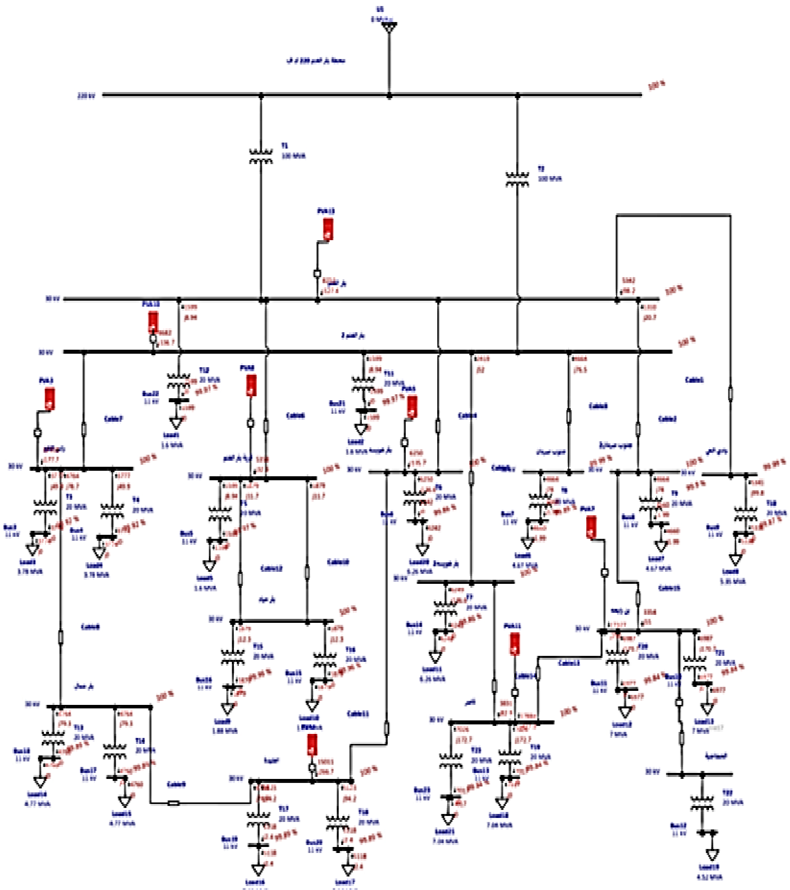

Figure 8. Bir al-Ghanim network in 2024 after optimization

6.5 Case III: 2029 Before Improvement

The 2029 demand is obtained by applying five years of 8% annual growth to the 2024 peak-load base. Without additional support, the higher demand increases current in the ring sections and deepens the voltage drop at remote buses. The violations shown in Figure 9 demonstrate that the 2024 improvement alone is not sufficient to absorb the projected growth through 2029.

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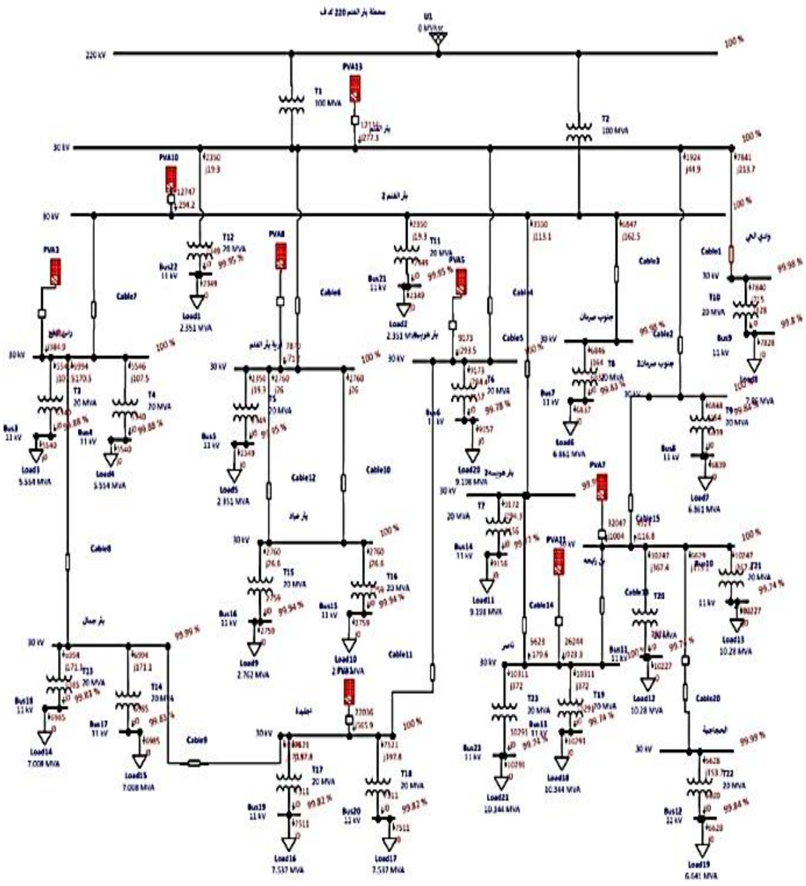

Figure 9. Forecast 2029 operating state before additional optimization

6.6 Case IV: 2029 After Improvement

Additional PV arrays are installed at critical points, including the Wadi Al-Hay feeder area, to support the buses affected by the projected demand increase. The post-improvement result in Figure 10 shows that the voltage and loading violations are removed or reduced to acceptable limits. The ETAP critical report reproduced in Table 1 lists the PV array elements and their operating outputs in this scenario.

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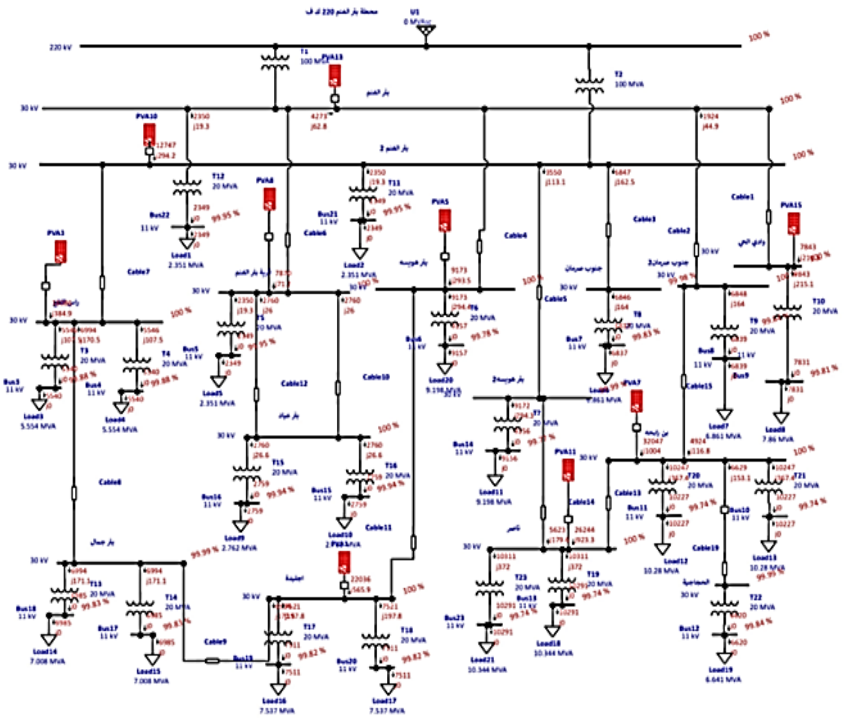

Figure 10. Forecast 2029 operating state after PV-based optimization

TABLE 1. ETAP critical report for the PV arrays used in the improvement case.

Device ID	Type	Condition	Rating/Limit	Unit	Operating	% Operating	Phase Type
PVA1	PV Array	Over Power	0.000	MW	15.011	104785100.0	3-Phase
PVA10	PV Array	Over Power	0.000	MW	8.682	60606330.0	3-Phase
PVA11	PV Array	Over Power	0.000	MW	17.884	124840300.0	3-Phase
PVA13	PV Array	Over Power	0.000	MW	8.252	57602790.0	3-Phase
PVA3	PV Array	Over Power	0.000	MW	12.318	85983890.0	3-Phase
PVA5	PV Array	Over Power	0.000	MW	6.250	43626480.0	3-Phase
PVA7	PV Array	Over Power	0.000	MW	17.327	120956500.0	3-Phase
PVA8	PV Array	Over Power	0.000	MW	5.358	37401560.0	3-Phase

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6.7 Case V: 2034 Before Improvement

The ten-year projection for 2034 produces a substantially higher network demand. Multiple feeders and buses exhibit voltage-drop or loading concerns, as shown in Figure 11. The result confirms that the growth trajectory creates a progressive need for distributed support, conventional reinforcement, or a coordinated combination of both.

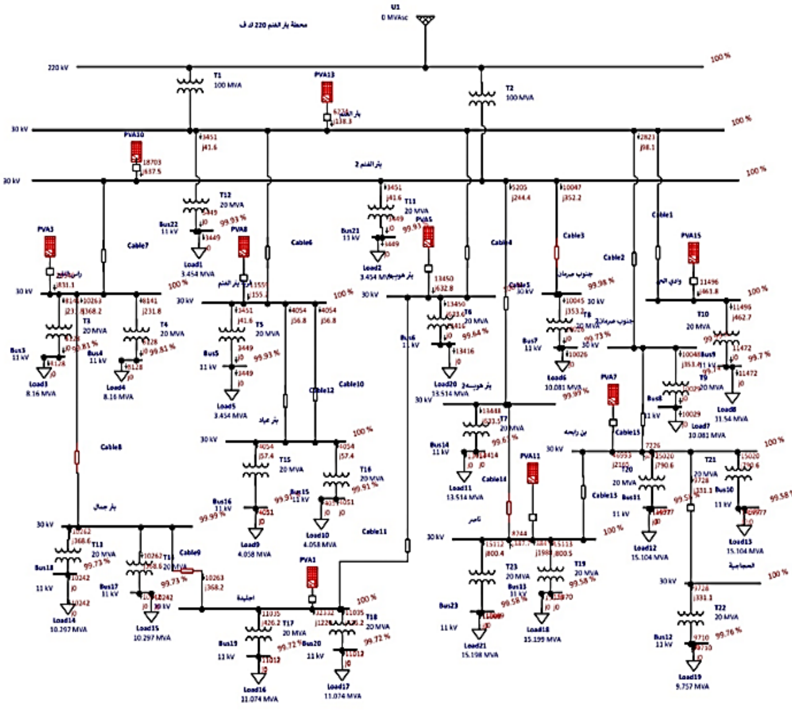

Figure 11. Forecast 2034 operating state before additional optimization

6.8 Case VI: 2034 After Improvement

Further PV capacity is added at the most sensitive buses in the 2034 case. The revised power-flow result in Figure 12 shows a more stable network with reduced voltage violations and less stress on the main ring branches. Although the final design would require detailed protection, short-circuit, harmonic, and economic studies, the result demonstrates the technical value of staged PV deployment as load grows.

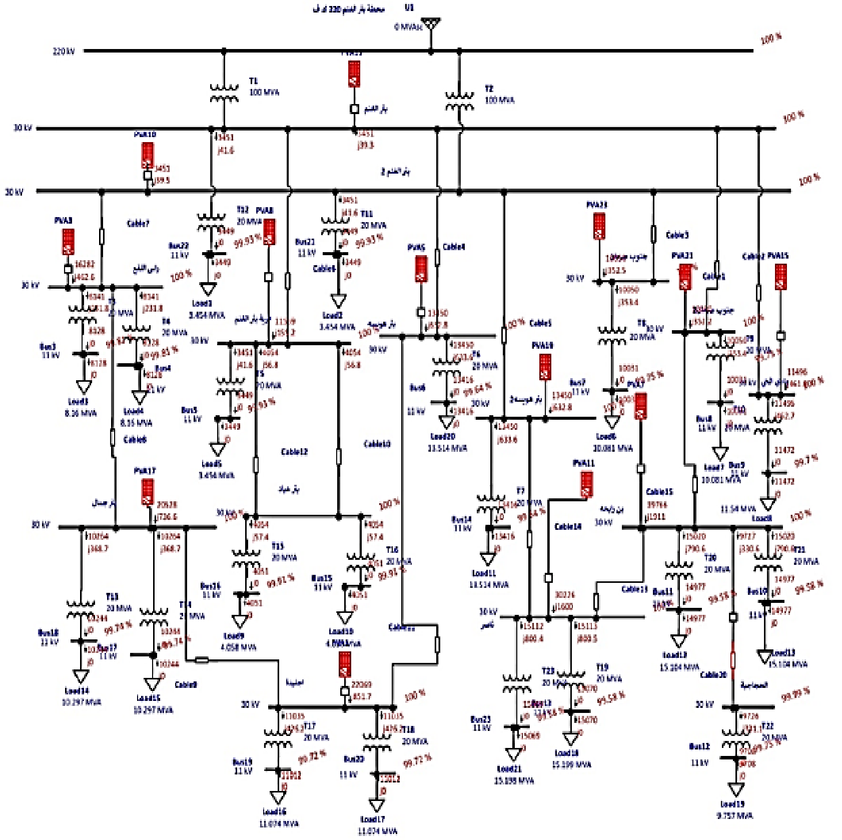

Figure 12. Forecast 2034 operating state after PV-based optimization

7. Discussion of Results

By implementing this approach, load growth can be effectively managed through the integration of photovoltaic (PV) modules at transmission lines prone to voltage drops or experiencing high loading conditions. This strategy illustrates that the deployment of distributed renewable energy generation can mitigate the need for expanding system cables and distribution substations, offering a more efficient and practical solution.

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The integration of PV systems into the grid provides several key advantages:

- **Voltage stability:** PV modules contribute to maintaining consistent voltage levels across the network, reducing fluctuations and enhancing overall reliability.
- **Overload mitigation:** Generating power closer to the consumption points alleviates stress on existing infrastructure.
- **Sustainability:** Incorporating solar energy reduces dependence on fossil fuels, supporting a cleaner and more environmentally sustainable energy mix.
- **Cost-effectiveness:** Installing photovoltaic systems can be more economical than extensive upgrades to traditional grid infrastructure, saving both time and financial resources.

8. Conclusion

This study investigates the application of modern techniques to enhance the 30 kV power system in the Bir Al-Ghanim grid and presents the outcomes of these improvements. It introduces a novel approach to power distribution aimed at optimizing and redesigning the network, supported by a detailed analysis and cost comparison based on both global market trends and local electricity utility data for 2024. The results indicate that the 30 kV network, being a critical component of the overall electricity grid, benefits significantly from upgrades and redesign, which reduce energy losses and increase operational flexibility. The implementation of photovoltaic (PV) penetration has shown superior performance, leading to a substantial reduction in energy losses and considerable cost savings, while also providing additional centralized generation capacity compared to traditional methods. Using this approach, energy losses can be reduced by more than 60%, and the environmentally friendly nature of PV technology offers an added ecological advantage, reinforcing its role in sustainable power system development.

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