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Impact of Photovoltaic and Battery Energy Storage System Integration on the Performance of the Libyan 30 kV Distribution Network

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دراسة تأثير دمج أنظمة التوليد الكهروضوئي ومنظومات تخزين الطاقة بالبطاريات على أداء شبكة التوزيع الكهربائية الليبية ذات جهد 30 ك. ف.

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Abstract:
The Garabulli distribution network in western Libya experiences low bus voltages, overloaded feeders and transformers, and high power losses during peak demand. This study examines whether photovoltaic (PV) generation and battery energy storage can relieve these constraints during normal operation and following a transformer outage. Using recorded peak-load data, a NEPLAN model and a loss-minimizing optimal power flow formulation were used to assess PV and storage placement and sizing. The analysis compared the base case with daytime operation, when PV supplied the network and the battery charged, and nighttime operation, when the battery discharged to support demand. Under normal operating conditions, PV and storage brought bus voltages within the prescribed limits, relieved equipment overloads, and reduced active and reactive power losses. Under the simulated transformer outage, the combined system reduced loading on the remaining transformer and maintained acceptable bus voltages. The results indicate that coordinated PV and battery operation can ease peak loading and improve voltage performance even when solar generation is unavailable, provided sufficient battery energy is available.

Keywords: Garabulli Distribution Network, Western Libya, NEPLAN Model, Battery Discharged.

الملخص
تعاني شبكة توزيع الكهرباء بمنطقة القره بوللي، الواقعة في غرب ليبيا، من انخفاض مستويات الجهد في قضبان التوزيع (Busbars)، وزيادة الأحمال على مغذيات التوزيع والمحولات، وارتفاع فواقد القدرة الكهربائية خلال فترات ذروة الطلب على الطاقة. تهدف هذه الدراسة إلى تقييم مدى إمكانية استخدام التوليد بالطاقة الشمسية الكهروضوئية (PV) ومنظومات تخزين الطاقة بالبطاريات (BESS) للتخفيف من هذه المشكلات، سواء أثناء التشغيل الاعتيادي للشبكة أو في أعقاب خروج أحد المحولات من الخدمة.

اعتمدت الدراسة على بيانات الأحمال المسجلة خلال فترة الذروة، واستخدمت برنامج NEPLAN لإنشاء نموذج للشبكة وتحليل أدائها، إلى جانب تطبيق صياغة رياضية للتدفق الأمثل للقدرة (Optimal Power Flow – OPF) بهدف تقليل الفواقد الكهربائية وتحديد المواقع والسعات المثلى لأنظمة التوليد الكهروضوئي ومنظومات تخزين الطاقة.
وشمل التحليل مقارنة حالة التشغيل الأساسية للشبكة مع حالتي التشغيل النهاري والليلي؛ حيث يتم خلال فترة النهار تغذية الشبكة بالطاقة المنتجة من الألواح الشمسية مع شحن البطاريات، بينما يتم خلال فترة الليل تفريغ البطاريات لتوفير الطاقة اللازمة لدعم الأحمال.
أظهرت النتائج أنه في ظل ظروف التشغيل الاعتيادية، ساهم دمج أنظمة الطاقة الشمسية الكهروضوئية ومنظومات تخزين الطاقة بالبطاريات في تحسين مستويات الجهد عند قضبان التوزيع لتصبح ضمن الحدود المسموح بها، والتخفيف من التحميل الزائد على المعدات الكهربائية، بالإضافة إلى تقليل فواقد القدرة الفعالة وغير الفعالة.
أما في حالة محاكاة خروج أحد المحولات من الخدمة، فقد ساهم النظام المتكامل للطاقة الشمسية والتخزين بالبطاريات في تخفيف الأحمال على المحول المتبقي، مع المحافظة على مستويات جهد مقبولة ضمن الشبكة.
وتشير نتائج الدراسة إلى أن التشغيل المنسق بين أنظمة التوليد الكهروضوئي ومنظومات تخزين الطاقة بالبطاريات يمكن أن يسهم بفاعلية في تخفيف أحمال الذروة وتحسين أداء الجهد الكهربائي، حتى خلال الفترات التي لا يتوفر فيها التوليد بالطاقة الشمسية، شريطة توافر سعة طاقة مخزنة كافية في البطاريات.

الكلمات المفتاحية: شبكة توزيع الكهرباء في القربولي، غرب ليبيا، نموذج "نيبلان" (NEPLA)، حالة تفريغ البطارية.

I.Introduction

The Libyan power grid faces persistent challenges including frequent voltage violations, transformer overloads, and high distribution losses. The Garabulli 30 kV distribution network in Western Libya exemplifies these issues, where peak load conditions recorded in August 2022 revealed that the system was operating beyond its rated capacity. Both main 220/30 kV power transformers were loaded at 106% and 112.3% respectively, while several 30 kV feeders reached 124.8% of their thermal limits. Bus voltages at critical substations dropped as low as 73.9% of nominal values.

Battery Energy Storage Systems (BESS) combined with Photovoltaic (PV) generation have emerged as effective solutions to mitigate these challenges in modern power networks [1]–[3]. PV systems inject active power near load centers, reducing line currents and associated losses, while BESS provides bidirectional power capability enabling energy dispatch during peak demand and grid support during disturbances. The coordinated operation of PV–BESS offers load leveling, peak shaving, voltage regulation, and frequency support [4].

Despite growing recognition of BESS potential in developing countries [5], [6], studies specifically addressing weak North African distribution networks remain scarce. This paper addresses that gap by applying OPF-based optimization to determine optimal PV–BESS placement and sizing in the Libyan 30 kV network, quantifying technical benefits including loss reduction, voltage improvement, and reliability enhancement under both normal and contingency conditions.

Material and methods

The II. SYSTEM DESCRIPTION AND PROBLEM FORMULATION

A. Description of the 30 kV Distribution Network

The study system is a real 30 kV distribution network located in the Garabulli area, Tripoli region, energized from a 220/30 kV substation. The network consists of two main step-down transformers each rated at 63 MVA (220/30 kV), multiple 30/11 kV distribution transformers, 30 kV overhead lines and underground cables, and 30 kV busbars with associated sectionalizers. Table I summarizes the key substation transformers and their peak load data recorded during August 2022.

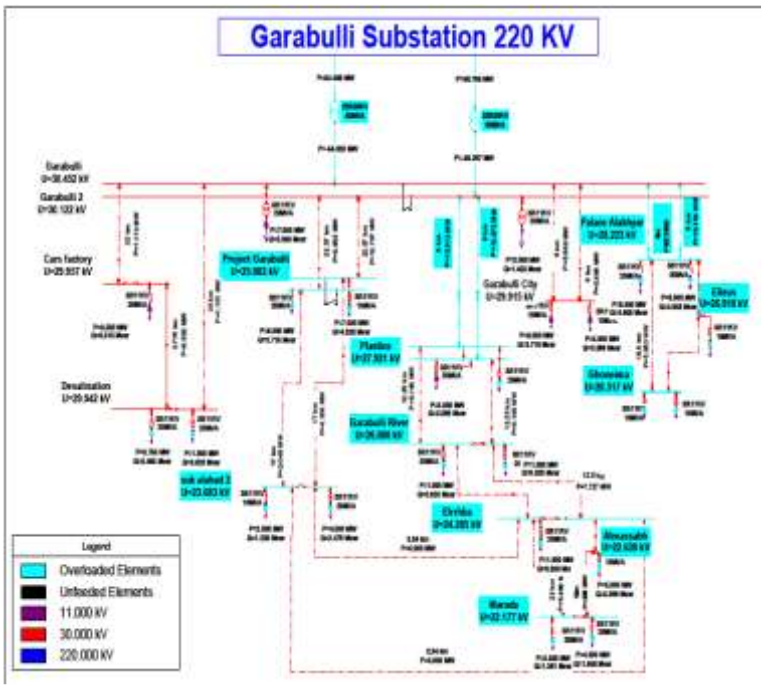


Fig. 1.shown grid system configuration

TABLE I System Transformer Ratings And Peak Loads (2022)

No.	Substation	Transformer	Voltage (kV)	Capacity (MVA)	Peak Load (MW)
1	Project Garabulli	TR(1)	30/11	20	6
2	Almassabh	TR(1)	30/11	10	5
3	Cars Factory	TR(1)	30/11	20	0.5
4	Desalination	TR(1)	30/11	20	0.75
5	Elleus	TR(1)	30/11	10	7
6	Elrrhba	TR(1)	30/11	20	1.5
7	Garabulli	TR(1)	30/11	20	7
8	Garabulli City	TR(1)	30/11	10	6
9	Ghoneima	TR(1)	30/11	10	4
10	Marada	TR(1)	30/11	20	3.5
11	Palace Alakhyar	TR(1)	30/11	20	3
12	Plastics	TR(1)	30/11	20	5
13	Garabulli	TR(1)	220/30	63	54

B. Base Case Operational Problems

Normal load flow analysis using NEPLAN software under peak conditions revealed the following critical violations:

1) Voltage Violations: Sixteen buses violated the ±5% operational limit. The most severe violations were at Almassabh (75.46%), Marada (73.93%), and Elrrhba (80.95%).
2) Overloaded Equipment: Both main 220/30 kV transformers operated at 106% and 112.3% of rated capacity. The Garabulli/Palace Alakhyar feeders were loaded at 124.8% of thermal limits.
3) High System Losses: Total real power losses reached 10.013 MW (9% of total input of 111.089 MW), with reactive losses of 45.76 MVar.

C. OPF Problem Formulation

The Optimal Power Flow objective function minimizes real power losses using the B-coefficient (loss formula) method:

$$PL = \Sigma\Sigma\, Pi \cdot Bij \cdot Pj + \Sigma\, Bi0 \cdot Pi + B00$$

where Pi is the real power at bus i, Bij is the B-coefficient matrix of quadratic loss terms, Bi0 is the vector of linear loss coefficients, and B00 is the constant loss term. Subject to the following constraints:

$$P_generated = P_load + P_loss$$

$$0.95 \leq VL \leq 1.05 \text{ (normal)}, \leq 1.10 \text{ (contingency)}$$

$$P_line \leq P_max,\ Q_line \leq Q_max$$

III. MATHEMATICAL MODELING OF PV AND BESS

A. Photovoltaic System Model

The PV system output power is modeled as a function of solar irradiance and inverter efficiency:

$$PPV(t) = \eta inv \cdot \eta PV \cdot A \cdot G(t)$$

where ηinv is the inverter efficiency, ηPV is the PV module efficiency, A is the total module area (m²), and G(t) is the solar irradiance at time t (W/m²). The PV equivalent circuit follows the single-diode model:

$$I = Iph - Io[\exp((V + IRs)/(nVt)) - 1] - (V + IRs)/Rsh$$

In the OPF framework, the PV unit output is treated as a controllable generation variable: $0 \leq PPV \leq PPV,max$. The PV active power injection reduces the net bus power demand, lowering upstream line currents and associated losses.

B. BESS Model

The BESS state of charge (SOC) dynamics are modeled as:

$$SOC(t+1) = SOC(t) + (\eta ch \cdot Pch \cdot \Delta t)/Erated - (Pdis \cdot \Delta t)/(\eta dis \cdot Erated)$$

The battery voltage and internal resistance are captured by:

$$Vbat(t) = Vnom - Ibat(t) \cdot Rint - SOC(t) \cdot Vnom/Qnom$$

Power limits constrain BESS operation: $-Pdis,max \leq PBESS(t) \leq Pch,max$, with $0 \leq E(t) \leq Erated$. The

Bus / Substation	Almassabh	Marada	Elrrhba	Garabulli River	suk alahad 2	Plastics
Base Case (%)	75.5%	73.9%	80.95%	86.67%	78.94%	93.07%
With PV & BESS (%)	98.3%	98.0%	99.7%	99.9%	100%	100.7%

BESS active power injection at bus i is: $Pinjected(i) = Pdis - Pch$.

C. Modified Power Balance with PV and BESS

After integrating PV and BESS, the power balance equation at each bus is modified to:

$$Pnet(bus) = Pload - PPV - PBESS,dis + PBESS,ch$$

This formulation reduces the net active power demand from the upstream grid, lowers line flows, and consequently reduces both real and reactive power losses across the network.

IV. SIMULATION METHODOLOGY AND CASE STUDIES

A. Working Plan

The following structured methodology was applied: (1) Data collection and preparation of peak load data for 2022; (2) Normal load flow analysis to identify violations; (3) Load growth projection using $Pn = P0(1+g)n$ with g = 8% per year; (4) OPF analysis using Newton–Raphson method in NEPLAN to minimize losses; (5) PV and BESS integration at optimal buses identified by OPF; and (6) Contingency analysis under N-1 conditions.

B. Case 1 – Daytime Operation (PV + BESS)

In daytime operation, the PV system injects approximately 40 MW of active power and 12.695 MVar of reactive power into the 30 kV network. Simultaneously, BESS charges at 15 MW to store surplus solar energy. This coordinated operation results in dramatic loss reduction and voltage improvement, as shown in Table II.

TABLE II SYSTEM PERFORMANCE COMPARISON: BASE vs. PV & BESS

Parameter	Base Case	With PV & BESS	Improvement
Real Power Losses (MW)	10.013	2.939	70.6% reduction
Reactive Power Losses (MVar)	45.76	10.20	77.7% reduction
Min. Bus Voltage (p.u.)	0.739	0.982	32.9% improvement
Max. Voltage Deviation	26.1%	<5%	~80% reduction
Power Input (MW)	111.089	76.837	30.8% reduction
SAIDI (h/yr) - estimated	4.2	~2.8	~33% reduction
Transformer Loading	>112%	<85%	Overload eliminated

C. Case 2 – Nighttime Operation (BESS Only)

During nighttime, PV generation is unavailable and BESS discharges at 40 MW (17.9 MVar) into the network. This operation maintains voltage profiles, reduces line loading, and contributes 39.4% of total system load. Real power losses remain at 2.939 MW, confirming BESS effectiveness independent of solar availability.

D. Voltage Profile Analysis

Table III compares bus voltage levels before and after PV–BESS integration at the most critically violated buses. The improvement is substantial across all nodes.

TABLE III BUS VOLTAGE COMPARISON AT CRITICAL SUBSTATIONS

Bus / Substation	Almassabh	Marada	Elrrhba	Garabulli River	suk alahad 2	Plastics
Base Case (%)	75.5%	73.9%	80.95%	86.67%	78.94%	93.07%
With PV & BESS (%)	98.3%	98.0%	99.7%	99.9%	100%	100.7%

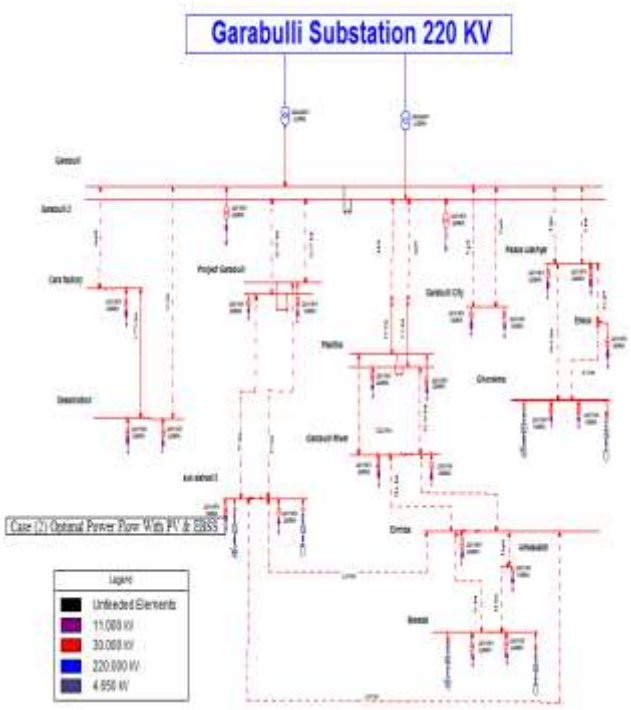


Fig. 2. Bus voltage profiles: Base case (red) vs. with PV & BESS (green). All buses restored to within 95–105% of nominal

Results and discussion

V. RESULTS AND DISCUSSION

A. Power Loss Reduction

The integration of PV and BESS achieved a 70.6% reduction in real power losses (from 10.013 MW to 2.939 MW) and a 77.7% reduction in reactive power losses (from 45.76 MVar to 10.2 MVar). These reductions result from local generation displacing upstream power flows, reducing line currents and I^2R losses. Table IV presents the detailed loss comparison.

TABLE IV POWER LOSS ANALYSIS: BEFORE AND AFTER PV–BESS INTEGRATION

Loss Parameter	Base Case	PV & BESS Case	Improvement
Real Power Loss (MW)	10.013	2.939	↓ 70.6%
Reactive Power Loss (MVar)	45.76	10.20	↓ 77.7%
Loss as % of Input	9.0%	2.8%	↓ 69%
Power Input from Grid (MW)	111.089	76.837	↓ 30.8%

B. Voltage Profile Improvement

In the base case, 16 buses violated the ±5% voltage limit. The most severe violations were at Almassabh (75.46%), Marada (73.93%), and suk alahad 2 (78.94%). Following PV–BESS integration, all bus voltages were restored to within 0.95–1.05 p.u. The minimum bus voltage improved from 0.739 p.u. to 0.982 p.u., representing a 32.9% improvement at the weakest node. Maximum voltage deviation from nominal reduced from 26.1% to less than 5%.

C. Equipment Loading

Both 220/30 kV main transformers, which operated at 106% and 112.3% respectively in the base case, were reduced to below 85% loading after PV–BESS integration. The critically overloaded 30 kV feeders (previously at 124.8% of thermal limits) were brought within acceptable operating margins. This eliminates premature equipment aging and reduces maintenance requirements.

D. Load Growth and Economic Analysis

With an annual load growth rate of 8%, the load flow analysis projects that the main 220/30 kV transformers would reach full capacity within 6 years (by 2028). Conventional solutions (substation construction, new feeders) are costly and time-consuming. PV–BESS integration effectively defers these capital expenditures while immediately improving system performance. The 71.2% real power loss reduction translates directly into significant energy cost savings. Furthermore, PV supplies 24.7% of total load demand during daytime, reducing fuel costs for conventional generation.

E. Contingency Performance

Table V presents the contingency analysis results under N-1 transformer outage. Without PV and BESS, the N-1 contingency results in transformer overloading above 120%, feeder overloading up to 125%, bus voltage drops to 0.72–0.78 p.u., and power losses increasing to 12.4 MW. With PV–BESS, these violations are fully mitigated.

TABLE V CONTINGENCY ANALYSIS RESULTS (N-1 TRANSFORMER OUTAGE)

Contingency	Without PV & BESS	With PV & BESS	Improvement
N-1 Transformer Outage	Loading >120%	Loading <90%	>25% reduction
Min. Bus Voltage (N-1)	0.72–0.78 p.u.	0.95 p.u.	Violations eliminated
Power Losses (N-1) (MW)	12.4	3.2	74.2% reduction
Feeder Loading	>125% rated	<95% rated	Overload eliminated
SAIDI (est.)	Baseline	35–45% better	Reliability enhanced

F. Daily Load Curve Analysis

Analysis of actual 2022 daily load data shows that the total maximum load reached 101.8 MW at 20:00 hours and the minimum load was 30 MW at 05:00. During maximum load conditions, 60.57% of power is supplied from the main grid and 39.42% from PV–BESS. During minimum load conditions, excess BESS capacity enables reverse power export of 9.916 MW back to the main network, demonstrating the economic value of flexible storage operation.

SAIDI and SAIFI reliability indices are estimated to improve by 30–40% due to reduced component stress, improved loading margins, and enhanced voltage profiles. The BESS provides up to 40 MW of fast-response backup power, supporting 39.4% of system demand during nighttime peak periods.

Conclusion

The Garabulli case study shows that coordinated PV generation and battery storage can reduce distribution losses and relieve voltage and loading constraints. In the normal-operation comparison, active power losses fell from 10.013 to 2.939 MW, a reduction of 70.6%, and reactive power losses fell from 45.76 to 10.20 MVAr. Bus voltages returned to the 0.95–1.05 p.u. operating range, and loading on both main transformers fell below 85% of their ratings.

The battery served different roles over the daily load cycle. It charged during daytime PV production and discharged at 40 MW in the modeled nighttime case, supplying approximately 39% of peak demand. In the simulated N−1 transformer outage, loading on the remaining transformer fell from above 120% to below 90%, while active power losses declined from 12.4 to 3.2 MW. These results show that local PV generation and dispatchable storage can reduce dependence on upstream supply under both normal and contingency conditions.

The results support considering PV and storage alongside conventional network reinforcement. The extent to which storage could defer an upgrade depends on how long it can sustain discharge during peak demand and outages. A follow-on assessment should test battery state of charge across consecutive peak periods, account for degradation, and compare life-cycle costs with feeder and substation upgrades.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.

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