

Reliability Assessment of a PV-Integrated 132 kV Power Network Using ETAP

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Abstract: This study presents a reliability assessment framework integrating ETAP simulations and probabilistic modeling to evaluate the reliability and operational impacts of photovoltaic (PV) integration on the Diyala 132 kV power network. The primary goal is to quantify the trade-off between improved reliability indices and operational shifts, such as altered power flows, loss reduction, and increased short-circuit fault currents. In this context, a reproducible methodology for assessing photovoltaic system reliability is presented, emphasizing probabilistic variations associated with photovoltaic power supplied through power electronic converter components. The study utilizes the Electrical Transient Analyzer Program (ETAP) for comprehensive network simulation, including load flow and short-circuit analysis. To model the stochastic nature of PV systems, a Capacity Outage Probability Table (COPT) based on the failure rates of power electronic components (e.g., DC converters, inverters) is linked to standard reliability indices. The integration of PV significantly alters network dynamics, notably reducing total apparent active power losses from 16.203 MW to 10.174 MW. However, PV penetration also increases short-circuit currents across the grid, necessitating adjustments to relay coordination to ensure protection. Furthermore, the results indicate that relay coordination adjustments may be required to mitigate increased fault currents while maintaining system efficiency. This research links component-level reliability analysis performed in MATLAB with system-level assessment conducted in ETAP, providing a reproducible methodology for evaluating PV-integrated grids. To enhance power system assessment, the proposed reliability framework provides information that may support relay coordination adjustment based on component failure characteristics.

Keywords: Reliability assessment, Photovoltaic systems, Power system reliability, ETAP, Short-circuit analysis, COPT.

1 INTRODUCTION

Renewable Energy (RE) sources, particularly wind and photovoltaic energy, have become essential for sustainable electricity production. However, the variability associated with these energy sources may influence overall system reliability. PV systems are vulnerable to component failures; faults in power electronic modules, including DC converters and control units, can significantly affect system availability [1]-[3]. A grid-connected PV system relies on PV modules to capture solar energy, DC choppers to process it, and inverters to convert the direct current (DC) into alternating current (AC). PV systems commonly employ DC-DC converter topologies such as Boost, Buck, Buck-Boost, and Cuk converters. Grid integration of photovoltaic systems requires DC-AC converters (inverters), which convert photovoltaic-generated DC power into AC power compatible with the electrical grid.

In general, photovoltaic systems are subject to multiple reliability challenges [4], particularly the solar cells and electrical equipment such as inverters [5]. In this study, inverter-related reliability indicators are used to evaluate PV system performance. Existing studies frequently focus on the reliability assessment of individual subsystems such as inverters, IGBTs, and capacitors [6], [7]. In contrast, there are limited publications addressing the reliability of integrated photovoltaic systems. In order to improve the photovoltaic system component reliability, this paper presents a COPT reliability model based on component failure rates and Mean Time Between Failures (MTBF). The COPT is a fundamental tool used in power system reliability studies.

1.1. Problem Statement

This research investigates the influence of photovoltaic integration on network reliability and protection performance under fault conditions. The growing deployment of Renewable Energy Sources (RES) significantly alters power system operational behavior. In conventional PV systems, DC choppers serve as the primary energy processing units; consequently, the reliability of these choppers strongly influences overall system availability of the PV system. Because renewable generation variability influences grid operation, PV systems remain vulnerable to component failure modes, particularly breakdowns in power modules such as defective DC converter connections or control unit faults. While existing research frequently isolates the reliability assessment of critical subsystems like Insulated Gate Bipolar Transistors (IGBTs) or inverters, comprehensive studies on the systemic reliability of interconnected PV systems remain limited.

1.2. Contribution

The primary objective of this study is to develop an integrated reliability assessment framework to evaluate the operational behavior and reliability of the Diyala 132 kV network in Iraq. By implementing a COPT model based on component failure rates, this research connects component-level and system-level reliability assessment indicators. Specifically, this work quantifies how varying PV penetration levels impact load currents, active/reactive power losses, and the pickup currents of overcurrent protection relays. Based on the established reliability metrics, converter topology performance is evaluated through reliability analysis of DC chopper and inverter configurations. The study evaluates the influence of PV penetration on feeder loading conditions and relay pickup current settings for overcurrent protection.

This study proposes an integrated assessment framework that evaluates the operational behavior and reliability of the Diyala 132 kV network in Iraq. The main contributions of this work are:

- **Analytical Integration:** Linking MATLAB-based converter reliability (Cuk vs. Buck-Boost) to ETAP system-level simulations via a COPT model.
- **Protection Optimization:** Providing reliability indicators that support relay coordination adjustment to balance fault mitigation with efficiency.
- **Reproducibility:** Demonstrating how component-level failures influence SAIFI, SAIDI, and CAIDI reliability indices.

2 RELATED WORK

Photovoltaic systems are increasingly adopted because of their low-emission electricity generation; however, reliability remains a critical factor affecting long-term deployment. Evaluating distribution network reliability has gained prominence due to the rising demand for continuous service with lower interruption frequencies and durations [8], [9]. Recent literature explores various strategies to optimize network performance. For example, improvements in Radial Distribution System (RDS) performance have been achieved using Optimal Capacitor Placement (OCP) and Distribution System Reconfiguration (DSR) through Multi-Objective optimization techniques. These methods enhance power quality by increasing bus voltages and decreasing power losses across standard IEEE test systems.

Additionally, integrating Distributed Generation (DG) requires specific reliability evaluation indexes and economic assessments, such as the Expected Cost of System Outage (ECOST) [10]. Simulation software plays a vital role in these evaluations. The ETAP spans the entire lifecycle of a power system and is widely used for modeling reliability improvements following DG deployment, as demonstrated in case studies utilizing the IEEE 9-bus system. Study [11] investigated distributed generation-integrated photovoltaic systems using reliability indices and energy cost assessment. ETAP simulation software is used to evaluate reliability indices relating to failure rate, mean annual power interruption time and repair time. The analytical method is used to assess the ECOST.

In [12], the paper reports a case study on the reliability assessment of the distribution system by deploying DG. Different scenarios are discussed and the system reliability improvement after the deployment of distributed generation is analyzed. An IEEE 9-bus system is investigated for the case study. ETAP (Electrical Transient Analyzer Program) software is used for reliability modelling and analysis. This powerful tool spans the entire lifecycle of an electrical power system, from initial concept and design to ongoing operations and maintenance. Its primary applications include power system analysis. To build a strong adaptive framework, a set of postulated failure current scenarios is meticulously constructed to enable the relays to be energized in the minimum possible time interval are presented in [13].

Recent studies proposed hybrid optimization algorithms combining Improved Harmony Search, Particle Swarm Optimization, and Differential Evolution to improve relay coordination performance. Simulation and evaluation results prove the efficiency of the hybrid algorithm in optimizing coordination between over-current relays to meet overriding system protection requirements. For the IEEE 6-bus system, the average 24-hour objective function value in Monte Carlo is 292.6607 and very close to 272.0758 in the simulation of 8 random scenarios, contributing to the approach's validity in practice.

Other research works in PV station reliability, covering issues such as component failures, environmental impact, reliability design, and sizing, are discussed in the following references [14]-[18]. Despite these developments, limited studies have integrated component-level PV reliability modeling with system-level ETAP reliability assessment under both load-flow and short-circuit operating conditions.

3 METHODOLOGY

This study presents a reliability assessment framework for evaluating the impact of photovoltaic integration on load-flow performance and short-circuit behavior. The framework integrates data collection, probabilistic failure modeling, and deterministic software simulation. The 132 kV network in the Diyala Governorate of Iraq serves as the primary case study. This network plays a crucial role in supplying power to the governorate and connecting it to the broader national grid. Reliability assessment of the Diyala grid requires evaluating operational performance and component outage behavior, which is crucial for ensuring a stable and continuous supply of electricity to the region. The proposed approach focuses on identifying the components that most significantly influence reliability, as well as the costs associated with current and future levels of reliability. The methodology consists of data collection, network modeling, probabilistic COPT analysis, and calculation of standard reliability indices.

3.1. Data Collection and Network Modeling

Studying the reliability of the Diyala grid requires targeting the most critical components impacting system stability. The data collection and preparation phase include:

- **Network Configuration:** The Diyala power network is modeled as a 47-bus network with 42 lines and 3 generator buses. It is fed by a 132 kV sub-transmission system via four main substations. The network generation capacity is modeled as 400 MW supplying a peak demand of 440 MW, with 10 MW of PV penetration (2.27%).
- **Component Characteristics & Outages:** Historical outage frequencies, component failure rates, repair times, and environmental conditions affecting reliability were compiled. Reliability inputs consisted of historical failure rates, PV penetration assumptions, and MTTR values.
- **Specific PV Failure Modes:** While IGBTs, capacitors, and relays are generic power electronics, they are central to PV inverters. Specific failure modes modeled include IGBT overvoltage (caused by switching transients or surges), IGBT overcurrent (caused by short circuits), and thermal cycling. Capacitor failures include electrolyte dry-out from excessive heat and dielectric breakdown from overvoltage stresses.

3.2. Linking COPT to Standard Reliability Indices

To perform reliability assessment, ETAP simulations are integrated with probabilistic COPT models. COPT is generated using MTBF and component failure rates to calculate the probability of varying states of PV power availability.

$$MTBF = \frac{1}{\lambda} \tag{1}$$

where λ is the failure rate. Reliability parameters generated through COPT are incorporated into ETAP simulations, which computes systemic impacts under stable conditions (Load Flow Analysis) and fault conditions (Short-Circuit Analysis). The framework explicitly translates these operational simulations into standard customer-oriented reliability indices, including SAIFI (System Average Interruption Frequency Index), SAIDI (System Average Interruption Duration Index), and CAIDI (Customer Average Interruption Duration Index). To ensure clarity, the following indices are defined prior to use.

$$SAIFI = \frac{\sum_{i=1}^n \lambda_i N_i}{\sum_{i=1}^n N_i} \tag{2}$$

$$SAIDI = \frac{\sum_{i=1}^n U_i N_i}{\sum_{i=1}^n N_i} \tag{3}$$

$$CAIDI = \frac{SAIDI}{SAIFI} \tag{4}$$

where λ_i is the failure rate, N_i is number of customers, U_i is annual outage duration, and n represents the total number of network components or customer groups included in the reliability assessment.

3.3. Reliability Improvement Strategies

Based on the assessment outcomes, several measures are proposed to improve the reliability of the Diyala network. These measures include strengthening the network through the addition of redundancy, such as parallel lines and network looping, as well as increasing equipment capacity where required. Reliability may also be improved by implementing more effective preventive maintenance programs and reducing repair times. In addition, equipment modernization through replacing ageing or less reliable equipment with more modern and reliable technologies can contribute to enhanced network performance. Further improvements may be achieved by optimizing protection and control systems through improving protection selectivity and response speed and implementing more efficient backup systems.

When studying the reliability of PV systems, it is crucial to understand the specific failure modes of their key components. Although IGBTs (Insulated Gate Bipolar Transistors), capacitors, and relays are generic components in power electronics, they are central to PV inverters and other conversion equipment, and their failures can significantly impact system performance and lifespan. For IGBTs in PV systems, common failure modes include overvoltage caused by switching transients, lightning-induced surges (via the panels), or faults on the AC grid. Overcurrent conditions may result from DC-side short circuits within the panels, AC-side grid faults, or incorrect switching operations. In addition, overheating and thermal cycling can further degrade component performance and reduce operational lifetime.

Similarly, capacitors in PV systems are exposed to several reliability challenges. Electrolyte dry-out may occur because of excessive ambient temperatures or capacitor losses that generate internal heat, as well as high ripple current conditions. Another important failure mode is dielectric breakdown, which may result from overvoltage, continuous voltage stresses exceeding equipment specifications, or manufacturing defects. Delamination may also occur and contribute to deterioration in long-term converter performance.

4 CASE STUDY: DIYALA NETWORK

4.1. ETAP-Based Reliability Assessment Procedure

The process for modeling the Diyala network and implementing reliability simulation using ETAP is divided into four steps:

Step 1: Data Collection and Preparation for the Diyala Network (see Table 1)

Step 2: Modelling the Network in ETAP

Step 3: Setting the Reliability Simulation in ETAP

This step involves defining system failure criteria and entering reliability parameters for each component.

Step 4: Analysis and Interpretation of Results

This step evaluates reliability indices including SAIFI (average interruption frequency), SAIDI (average interruption duration), and CAIDI (average interruption restoration duration).

Table 1. Data Collection and Preparation for the Diyala Network

Component	Failure Rate (λ /yr)	MTTR (hr)	MTBF (hr)
PV Inverter	0.50	24	17520
DC/DC Converter	0.45	15	19466
Circuit Breaker	0.02	10	438000
Transformers	0.015	72	584000
Lines	0.1	8	87600

This structured approach supports a systematic assessment of Diyala network reliability. As indicated in Fig. 1, the Diyala energy system illustrates the interconnections between various substations and power facilities, forming a part of an electrical transmission grid. It represents the electrical topology used for ETAP-based network analysis. The modeled network consists of a realistic 47-bus electrical system. The network contains 42 transmission lines, 47 buses, and 3 generator buses and is supplied through a 132 kV sub-transmission system via four large substations connected at nodes 2, 17, 34, and 39. Between 132/11 kV and 30 MVA supply substations 2 and 17, respectively, are transformers for supply substations of 132/33 kV and 45 MVA. Bus 1 is defined as the swing (slack) bus for power flow calculations. Transmission line losses are included in the simulation. The total producing capacity of the Diyala 132 kV network is modeled at 400 MW supplying a peak demand of 440 MW. The network includes integration of 10 MW photovoltaic generation and operates at an apparent power level of 435.294 MVA. Relay parameter values used in the simulation are summarized in Table 2, based on the IEEE standard inverter ratings.

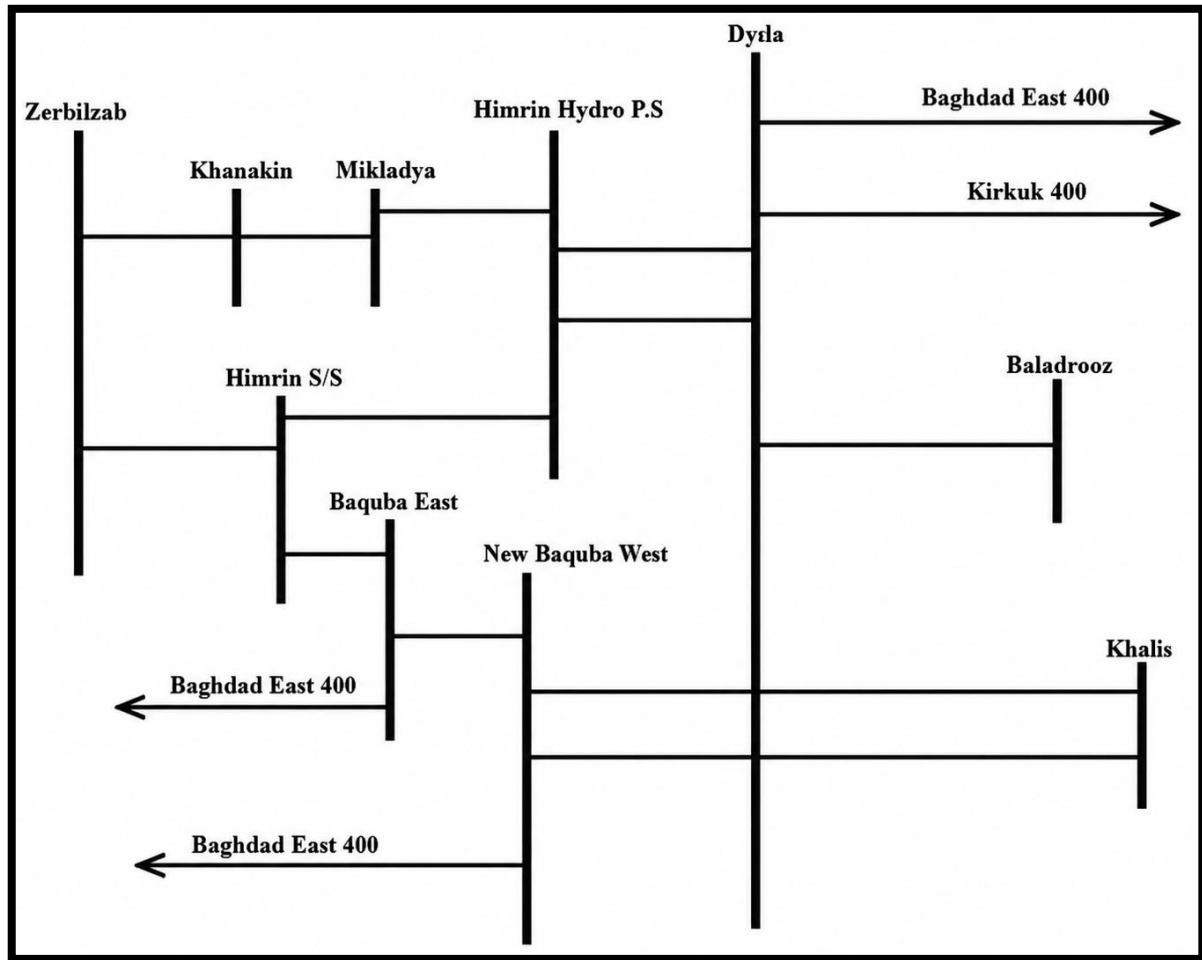


Fig. 1. Diyala network 132 kV

Table 2. OC relay inverter specifications

Specifications of OC relay Inverter	CT	Ip	TMS	Delay setting (sec)
10% to 30% from rating power	300/5	5	0.3	0.08
30% to 70% from rating power	500/5	5	0.2	0.06
70 to 100% from rating power	600/5	5	0.1	0.04

4.2. Load Flow Results

The integration of photovoltaic generation into the network influences power flow characteristics and may improve operational performance, as illustrated in Fig. 2. Fig. 2 illustrates the ETAP simulation model used for electrical network analysis, including:

- Load flow analysis: for determining voltages, currents, and power flows throughout the network under stable conditions.
- Short-circuit analysis: for computing fault currents at various locations and coordinating protective devices.
- Reliability studies: to evaluate the effect of component outages on system performance.
- Voltage stability analysis: to ensure that voltage levels remain within acceptability limits.

The addition of PV generation can improve operational efficiency by supplying active power locally and reducing transmission loading and associated losses.

- **Loss Reduction:** ETAP load flow analyses demonstrate that prior to PV integration, total apparent active power losses were 16.203 MW. Following PV integration, these losses decreased to 10.174 MW, indicating improved network operating efficiency under simulated conditions.
- **Power Flow Adjustments:** The inclusion of a PV system changes power flow distribution across the network, altering the power flow direction and magnitude, effectively decreasing the baseline line load.

The simulation results suggest that PV integration may reduce reactive power demand and improve operating conditions. Reactive power requirements are reduced via decreased reactive power losses in the network. Tables 3, 4 and 5 compared the electricity flow in a Diyala electrical network prior to and after the installation of a PV system. It analysed the impact of solar energy integration on several electrical parameters at the network's various locations. These Tables demonstrate the influence of photovoltaic integration on network power flow characteristics. It alters the power flow direction and magnitude, decreases the line load, and impacts operational characteristics such as the current and power factor within the network.

According to Tables 3–5, the power flow results before and after PV integration are summarized. Table 4 indicates changes in reactive power distribution under PV-integrated operating conditions. The power flow values indicate altered active and reactive power distribution after PV integration. The results suggest that PV integration improves operating efficiency by providing active power locally. Load flow results show that total active power losses decreased from 16.203 MW to 10.174 MW after PV integration, corresponding to an approximate 37.2% reduction.

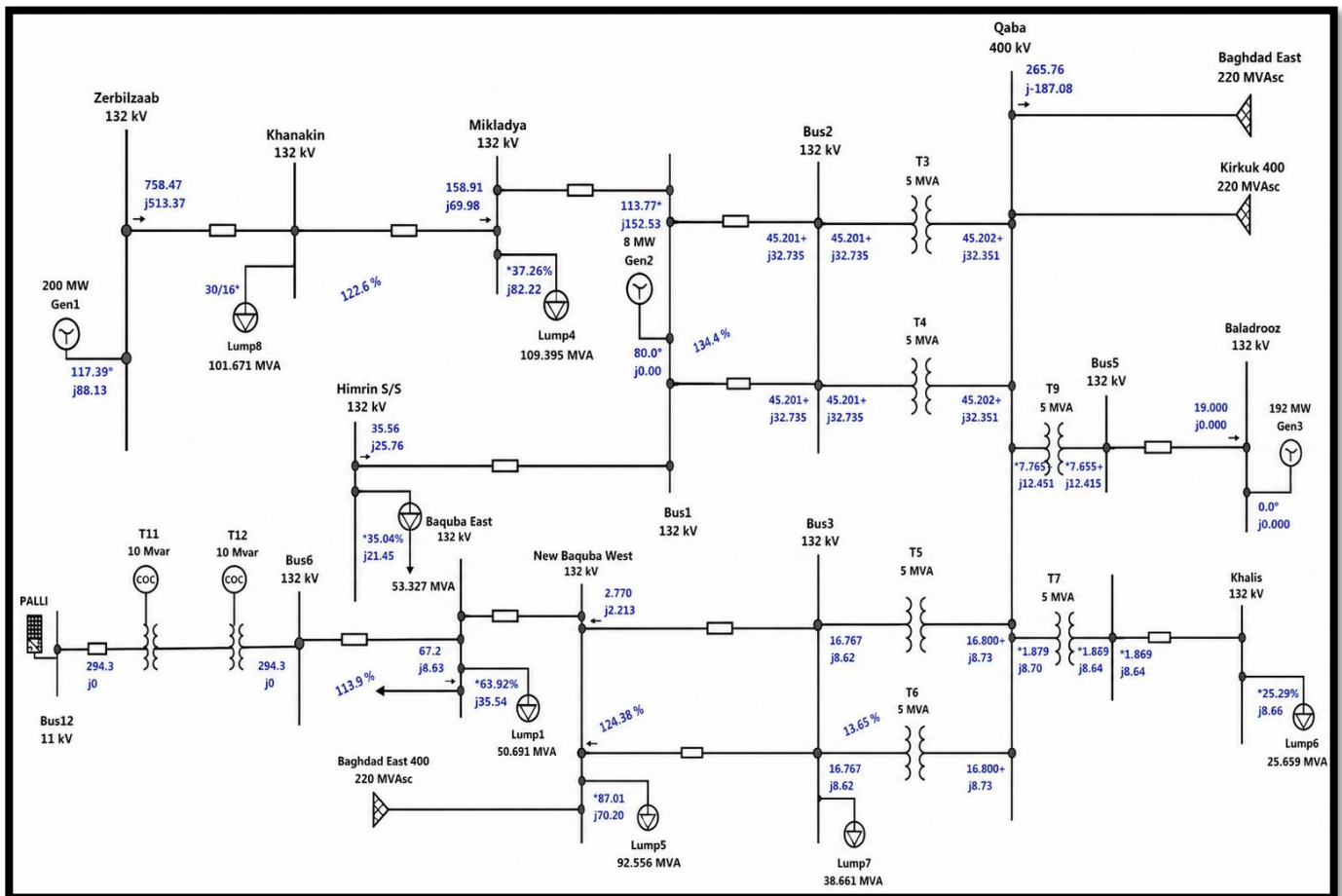


Fig. 2. Power Flow Simulation of the Diyala Network by ETAP Program

The chosen system, which uses a model predictive-based Cuk converter and a solar energy system-based on 3 phase inverter control, is subjected to a reliability study. A Cuk converter is defined as a switching-mode DC-DC converter that uses a capacitor as its primary energy storage and transfer element between the input and output, unlike buck and boost converters which primarily use inductors for energy storage. The component-level reliability analysis performed in MATLAB (comparing Cuk and Buck-Boost topologies) serves to define the failure rate parameters for the PV system. These parameters are then utilized as inputs for the ETAP reliability assessment, ensuring that the system-level indices reflect the assumed reliability characteristics of the power electronics used. The integration of PV units reduced active power losses from 16.203 MW to 10.174 MW, corresponding to an approximate 37.2% reduction in active power losses.

Table 3. Power Flow Bus without PV

Fault location without PV	MW	Mvar	Amp	% PF
Baladrooz	190.000	20.000	557.1	99.5
Baquba East	-0.294	-2.558	8.1	11.4
1 Bus	-44.888	-34.224	183.6	79.5
2 Bus	45.981	32.755	178.9	81.4
3 Bus	-2.763	-4.758	17.4	50.2
4 Bus	11.861	6.964	43.4	86.2
5 Bus	-179.658	-13.415	557.8	99.7
6 Bus	0.294	0.000	0.9	86.4
12 Bus	0.294	0.000	11.1	99.6
Diyala	46.302	32.851	59.1	81.6
Himrin S/S	-37.816	-27.521	150.4	80.9
Khalis	-11.791	-9.433	48.0	78.1
Khanakin	-15.567	-11.241	63.3	81.1
Mikdadya	-112.978	-91.229	474.6	77.8
New Baquba West	2.770	2.213	11.2	78.1
Zerbilzabh	38.546	25.676	145.8	83.2

Table 4. Power Flow Results for Network Buses with PV Integration

Fault location with PV	MW	Mvar	Amp	% PF
Baladrooz	0.294	0.000	0.9	99.6
Baquba East	0.001	-2.558	8.1	12.7
1 Bus	-47.120	-34.683	190.6	80.5
2 Bus	45.991	32.759	179.0	81.5
3 Bus	-2.742	-4.751	17.3	50.0
4 Bus	11.861	6.964	43.4	86.2
5 Bus	-179.658	-13.415	557.8	99.7
6 Bus	0.294	0.000	0.9	86.4
12 Bus	0.294	0.000	11.1	99.6
Diyala	46.302	33.400	61.4	82.4
Himrin S/S	-37.706	-27.521	150.1	80.8
Khalis	-11.645	-9.433	47.6	77.7
Khanakin	-15.453	-10.805	58.6	79.3
Mikdadya	-112.746	-90.722	469.8	77.5
New Baquba West	-26.350	2.213	11.2	78.1
Zerbilzabh	-32.697	-28.584	148.2	75.6

Table 5. Electricity flow following and prior to PV system connection

	Source (Swing Buses)		Total Demand		Apparent Losses	
	MW	Mvar	MW	Mvar	MW	Mvar
Before PV	390.702	286.995	390.996	286.995	16.203	-7.043
After PV	478.455	327.620	468.575	318.622	10.174	8.998

5 RESULTS AND DISCUSSION

5.1. PVs Effect on Short Circuit Faults

To maintain protection selectivity after PV integration, the relay pickup currents (I_{pickup}) were recalculated to account for the increased fault current, particularly at Bus-12 where I increased to 34.335 kA. The relay operation follows the Inverse Definite Minimum Time (IDMT) characteristic:

$$t = TMS \times \frac{k}{\left(\frac{I}{I_{pickup}}\right)^\alpha - 1} \tag{5}$$

where t is relay operating time (s), TMS is Time Multiplier Setting, I is the fault current, I_{pickup} , k, and α are the relay characteristic constants.

This section evaluates the impact of photovoltaic integration on short-circuit behavior. Fig. 3 illustrates the PV effect on bus 12 after a short-circuit fault. The minimum and maximum short circuits for each bus after and before installing PV are displayed in Tables 6 and 7. While PV integration improves steady-state operating performance, it modifies system behavior under fault conditions.

- **Fault Current Increase:** Simulation results show a marked increase in short-circuit currents across multiple buses. For example, at Bus 12, the maximum fault current without PV was 7.459 kA. With the PV system connected, the maximum fault current surged to 34.335 kA, (Tables 6 and 7).
- **Relay Coordination Implications:** This increase in short-circuit currents indicates that existing protective devices (circuit breakers and fuses) may require reassessment and coordination adjustment, Tables 6 and 7. Relay coordination settings should be reviewed under the new PV penetration conditions to prevent momentary power surges (inrush currents) from causing system damage.

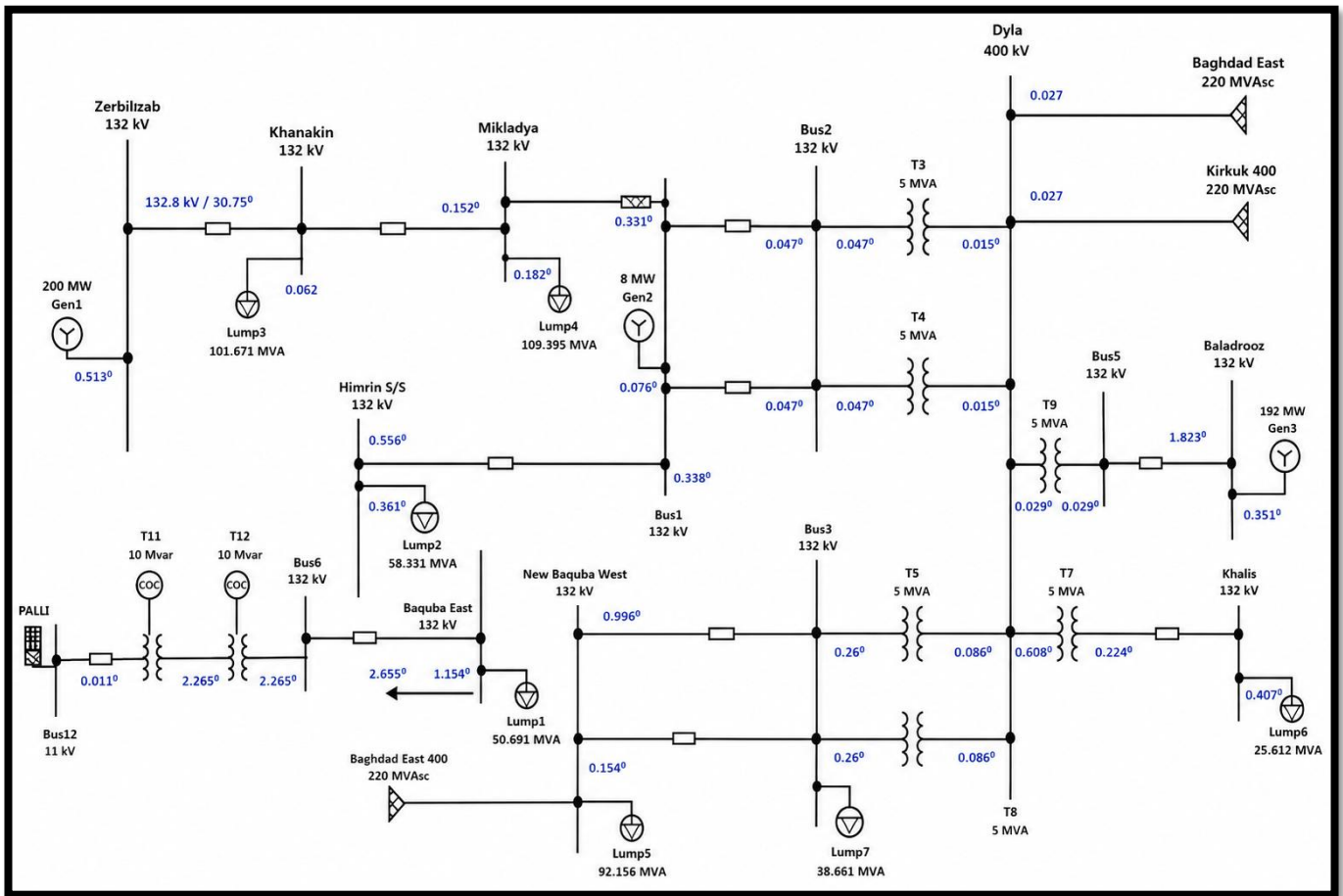


Fig. 3. Diyala network after fault simulation by the ETAP programme

Tables 6 and 7 present short-circuit current results for the Diyala electrical network under operating conditions without and with photovoltaic integration. For the Power Flow Analysis, the Tables 3, 4 and 5 compared the standard operating conditions of the electrical Diyala network before and after the PV system connection for each location. Tables 6 and 7 compare the minimum and maximum short-circuit currents under conditions without and with PV integration. These values are crucial for the design and sizing of protective equipment (circuit breakers, fuses). The significant increase in fault current at Bus 12 (from 7.459 kA to 34.335 kA) following PV integration is attributed to the increased equivalent fault contribution following PV integration and the resulting decrease in equivalent grid impedance. These results indicate that breaker interrupting capacities and relay settings should be evaluated and relay pickup settings may require recalculation to maintain protection selectivity and prevent equipment damage.

Table 6. Short-circuit results for each bus excluding PV

Fault location without PV	$I_{(Max)}$	$I_{(Min)}$
Himrin S/S	7.671	6.754
Khanakin	6.017	5.198
2 Bus	4.950	4.621
3 Bus	3.721	3.490
4 Bus	14.208	11.289
6 Bus	4.431	3.959
12 Bus	7.459	6.341
Khalis	5.061	4.526
Mikdadya	7.299	6.261
5 Bus	13.693	11.557

Table 7. Short-circuit results for each bus with PV

Fault location with PV	$I_{(Max)}$	$I_{(Min)}$
Himrin S/S	10.476	7.986
Khanakin	9.239	6.588
2 Bus	11.959	9.012
3 Bus	11.661	8.695
4 Bus	10.434	8.062
6 Bus	3.039	2.699
12 Bus	34.335	30.631
Khalis	5.485	4.523
Mikdadya	11.819	8.104
5 Bus	11.021	8.938

5.2. DC Converter Reliability Assessment

Converter reliability refers to the ability of a photovoltaic power conversion system to operate under specified conditions without failure over a defined period. Different DC converter topologies were evaluated for efficiency under varying solar irradiation. A buck-boost converter offers flexibility by either increasing or reducing input voltage, which is highly beneficial for sustaining desired output voltages under fluctuating solar radiation while enabling Maximum Power Point Tracking (MPPT). However, the Cuk converter, defined as a switching-mode DC-DC converter that uses a capacitor as its primary energy storage and transfer element, demonstrated improved operating stability under the simulated conditions. The Cuk converter configuration showed improved performance indicators and stabilization across the irradiation spectrum compared to standard boost and buck-boost configurations.

Fig. 4 illustrates the PV output variation obtained using the DC boost converter under varying operating conditions. This graph therefore illustrates the dynamics and stabilisation of the output power of a photovoltaic unit integrated with a DC boost chopper, presumably thanks to the use of an MPPT algorithm that optimizes power extraction. Yield analysis estimated a Total Array Yield (YA) of 19.456 kWh/day, Fig. 5b. Tracking this reference efficiency data allows operators to identify specific undesirable events, such as DC converter operating modes or faulty diodes and transistors, when overall system efficiency drops. The component-level reliability analysis conducted in MATLAB (comparing Cuk and Buck-Boost topologies) provides the failure rate inputs used in the ETAP COPT model. This ensures that the system-level reliability indices calculated in ETAP reflect the assumed converter reliability characteristics of the chosen converter technology. A simulation study was conducted using 50 parallel strings and 10 series-connected modules per string. The MATLAB environment was used to develop the system and draw results.

The simulated PV system was evaluated using commonly used DC converter topologies to compare output performance. PV systems can only produce electricity when solar radiation is present. Fig. 4 presents the PV output power connected to the DC chopper boost converter. Fig. 5(a) and 5(b) display the corresponding output characteristics. as functions of duty cycle and load voltage. A buck-boost converter is a DC-DC converter that can either increase (boost) or reduce (buck) input voltage. This flexibility is particularly beneficial for photovoltaic systems, as photovoltaic voltage can fluctuate significantly depending on solar radiation and temperature, and the buck-boost can sustain a desired output voltage to the load whilst enabling maximum power point tracking (MPPT). The PV solar radiation output supplied to the buck-boost converter and Cuk Chopper is depicted in Fig. 5(a) and Fig. 5(b), respectively.

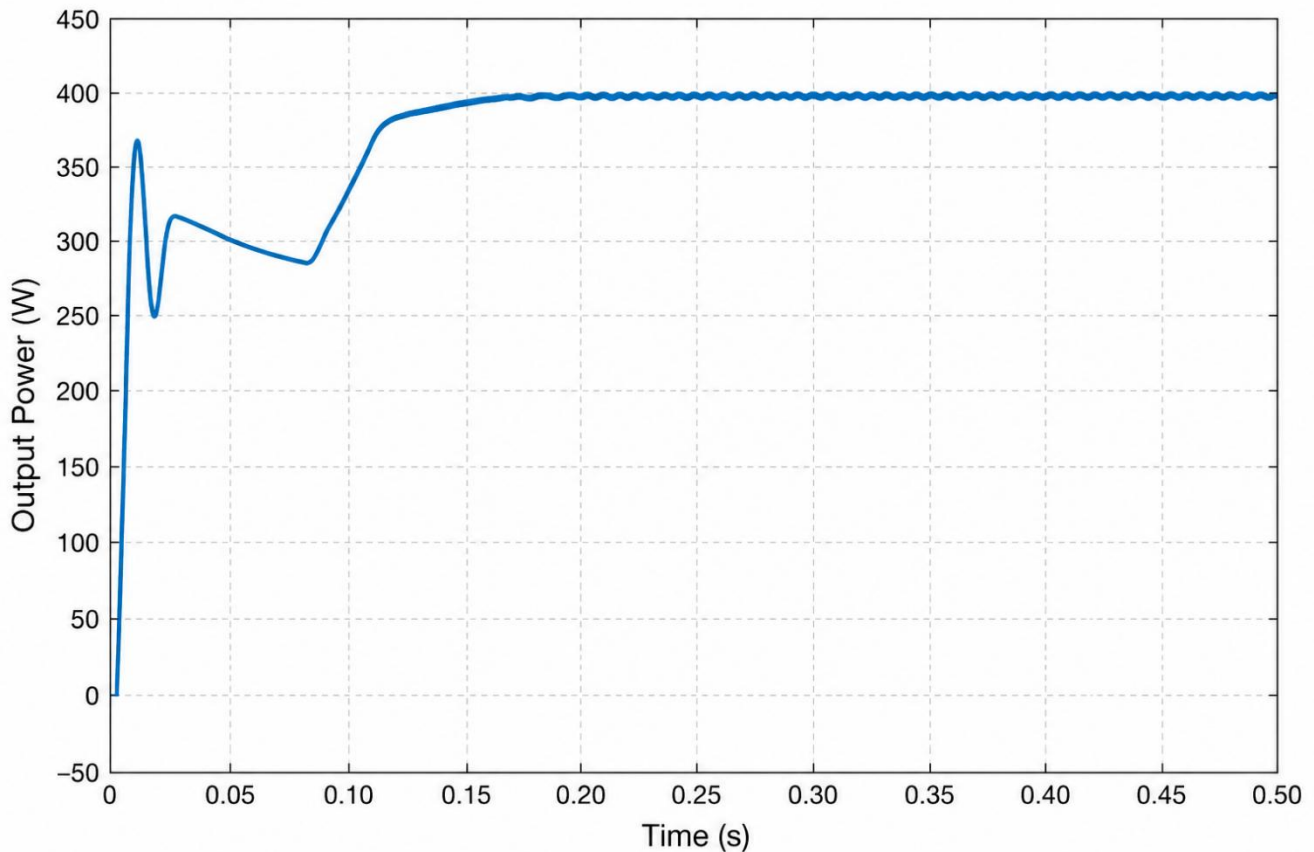


Fig. 4. Photovoltaic unit output power connected to a DC boost chopper

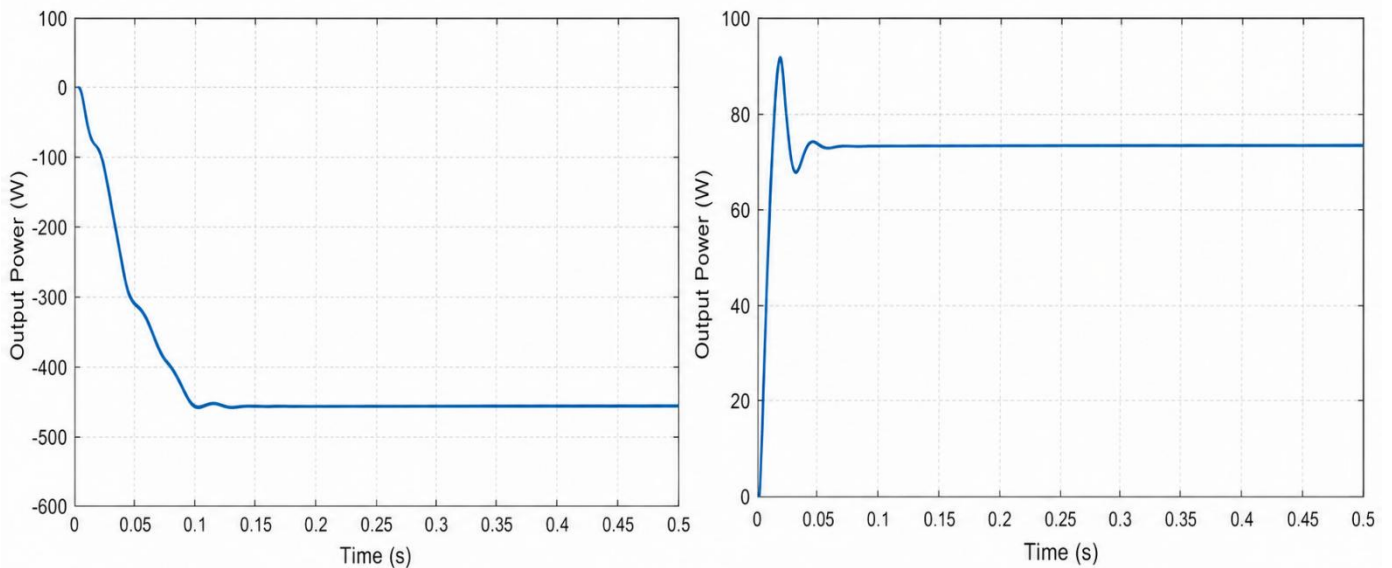


Fig. 5. PV Unit Output Power a) connected to a buck-boost DC chopper, b) after connecting the Cuk chopper

Table 8 provides an analysis of various operating states of a power generation system, correlating the number of units out of service, the total unavailable capacity, the output power, the probability of this state occurring, and performance measures. This table is very useful for studying the reliability of a Diyala power system. So, in this table, radiation during an outage is depicted, along with a probability assessment depending on the elevated radiation increasing by 10% per step until it reaches its highest value of 100%. The outcomes of daily average energy output, PV module and array yield, reference yield, performance ratio, and system losses for 10 distinct PV module systems are also discussed.

The reference efficiency data presented in Table 8 can be used to identify if the system is operating as intended and to pinpoint DC converter operating modes, faulty diodes, transistors and capacitors in PV modules. Significant decreases in efficiency involve the undesirable events affecting PV performance, such as DC converter failures. The Total Array Yield (YA) equal to 19.456 kWh /day is used to assess solar radiation performance. Fig. 6 compares PV output power variation across different DC converter topologies. In fact, the photovoltaic output power increases with increasing power demand in all DC converter configurations. Fig. 6 suggests improved output characteristics of the Cuk converter configuration under the simulated operating conditions. In conclusion, the output power variation of a DC chopper integrated into a photovoltaic system mainly depends on the solar radiation. Different chopper topologies (Boost, Buck-Boost, Cuk) have different efficiencies and outputs depending on the irradiation spectrum. So, Fig. 6 provides a comparative analysis of performance, showing the efficiency of different converter topologies.

Table 8. PV Production Probability and Yield Indices

Units in outage	Capacity in outage	Hours	P_{output} Array	Probability	Reference Yield	Array Yield
1000	0	9	9.794×10^4	0.86694720	8.73	0.184
900	100	4	8.859×10^4	0.04562880	3.44	0.205
800	200	4	7.893×10^4	0.03612280	3.156	0.232
700	300	3	6.938×10^4	0.02871400	2.07	0.266
600	400	2	5.963×10^4	0.01910400	1.18	0.313
500	500	1	4.94×10^4	0.00204840	0.49	0.378
400	600	1	3.96×10^4	0.00079600	0.39	0.477
300	700	0	2.421×10^4	0.00058600	0	0.644
200	800	0	1.086×10^4	0.00002880	0	0.982
100	900	0	2747	0.00002280	0	2.043
0	1000	0	0	0.00000120	0	0

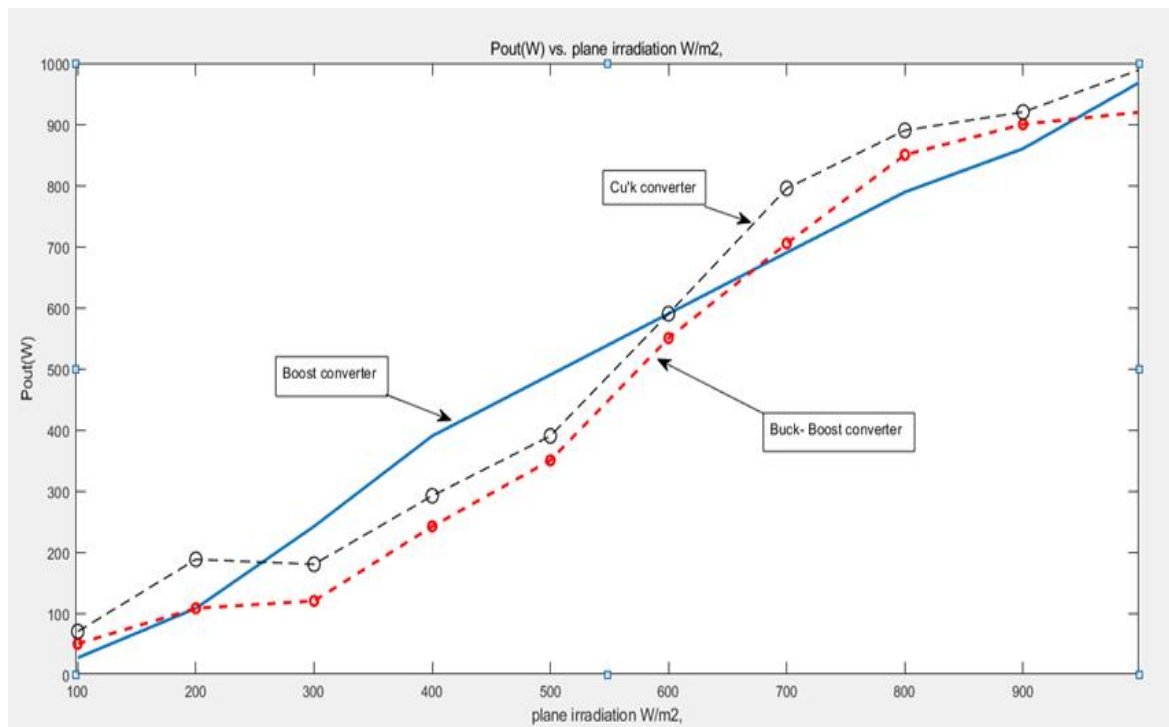


Fig. 6. Compare variation output power of PV integrated dc chopper

Table 9. Reliability Indexes

Reliability Index	Base Case (No PV)	With 10 MW PV	Improvement (%)
SAIFI (f/customer.yr)	35.9181	31.1897	13.17
SAIDI (hr/customer.yr)	383.1364	312.587	18.57
CAIDI (hr/customer.int)	10.667	8.445	20.7

The integration of 10 MW PV power into the Diyala 132 kV power network results in a measurable enhancement across all standard reliability indicators, as summarized in Table 9. The quantitative results are summarized as follows:

- SAIFI (System Average Interruption Frequency Index): The frequency of interruptions decreased from 35.9181 to 31.1897 occurrences per customer/year. This 13.17% improvement indicates that the presence of localized PV generation helps stabilize the grid and reduces the number of failure events experienced by end-users.
- SAIDI (System Average Interruption Duration Index): The total duration of interruptions dropped from 383.1364 to 312.587 hours per customer/year. This 18.57% reduction demonstrates a significant increase in overall system availability and a reduction in the total time customers are without power.
- CAIDI (Customer Average Interruption Duration Index): The average time required to restore service during an interruption improved from 10.667 to 8.445 hours. This represents the most significant improvement (20.7%), suggesting that PV integration provides critical support that minimizes the impact of individual outages.

The results suggest that the hybrid deterministic-probabilistic approach integrating COPT and system-level simulations provides a useful framework for evaluating PV integration. The reduction in SAIFI, SAIDI, and CAIDI confirms that the proposed PV integration strategy successfully enhances the resilience of high-voltage distribution networks.

5.3. Comparative study

To provide comparative context, reliability indicators of the Diyala network were compared with reported values from the Dangila (Ethiopia) network. While Dangila reports a higher SAIFI value (693.5) than Diyala (35.9181), the comparison suggests differences in interruption frequency under the reported operating conditions. This comparison provides contextual understanding of reliability improvement opportunities. Direct comparison between Dangila and Diyala should be interpreted cautiously because of differences in operating conditions, data sources, system configurations, and the availability of reliability information. Reported reliability assessment results for the Dangila substation (2020–2024) indicate the following baseline reliability indices (Table 10):

- SAIFI (System Average Interruption Frequency Index): 774.93 interruptions per customer per year.
- SAIDI (System Average Interruption Duration Index): 1231.48 minutes per customer per year.
- CAIDI (Customer Average Interruption Duration Index): 1.589 hours per interrupted customer.

Based on the reported reliability indices:

- The reported reliability indices indicate lower interruption performance for the Dangila network than the Diyala case considered in this study. Previous studies have investigated distributed generation integration as one approach for improving reliability performance.
- The Diyala system demonstrates moderate reliability based on the evaluated indices.

Both systems present reliability challenges under their respective operating environments. However, the reported data for Dangila provides quantified reliability indices, whereas the Diyala analysis focuses on system operating performance and network reliability assessment. Based on the reported indices, the Dangila network exhibits higher interruption indicators than the Diyala case examined in this study.

Table 10. Reliability Indices of Diyala and Dangila Systems

	Diyala	Dangila
CAIDI	10.667	1.635
SAIDI	383.1364	1134.2
SAIFI	35.9181	693.5

The second part of this section is intended to illustrate the extent to which this study bridges gaps in prior research by comparing our findings with previous studies. This section benchmarks the reliability characteristics of the Diyala power network against comparable case studies reported in the literature. Previous reliability studies commonly employ probabilistic modeling and network analysis to identify power distribution failure points [18]-[20]. These studies revealed that power failures were more prevalent in extreme weather conditions. The proposed remedies include back-up systems and improvements to the infrastructure to ensure greater resistance to weather conditions.

To contextualize network performance, the reliability indices of the Diyala power system were benchmarked against the Dangila network in Ethiopia.

- **Dangila Network:** Exhibits weak reliability with a SAIFI of 693.5 and a SAIDI of 1134.2, indicating highly frequent and prolonged outages.
- **Diyala Network:** Demonstrates significantly better baseline metrics with a SAIFI of 35.9181 and a SAIDI of 383.1364. While Diyala faces moderate reliability issues characterized by daily outages and a gap between electricity supply and demand, the quantitative indices confirm a stronger infrastructure than comparative developing networks.

Previous studies in regions such as Nairobi [19], Kirkuk [20], and Kigali [21] focused primarily on reliability evaluation rather than optimization-oriented assessment at the planning stage. This study extends prior work by incorporating component failure probabilities into reliability evaluation. Another contribution of this study is that several estimated parameters are computed on the basis of the solar power generation capacity levels and failure conditions. Reliability indices such as average unsupplied energy and loss of load forecast are computed based on this probability, as well as indices such as CAIDI, SAIFI and SAIDI from customers engaged in evaluating the Reliability of distribution networks, including PV. Future reliability improvement strategies may include improved weather resilience measures, backup systems, and alternative energy integration. The installation of backup generators and alternative energy sources (e.g. solar or energy storage) might also provide a solution for increasing the distribution network's resilience in Diyala. In summary, the main goal of this study was to increase the effectiveness of the Diyala Electric Power (132 KV) system. The technique used for power plants in Iraq employed the indicated analytical approach for evaluating the reliability and efficiency of the PV system's parts. The first of the two key contributions is a method for estimating the dependability of PV levels based on power loss, and the second considers system component outages depending on the failure rate of power electronic components in a PV system. To the authors' knowledge, similar integrated reliability assessment studies for the Diyala power system remain limited.

6 CONCLUSION

This study evaluates the reliability impacts of PV integration in the Diyala 132 kV network. Load flow analysis indicates an approximate 37% reduction in active power losses, while short-circuit analysis indicates increased fault currents that may require relay coordination adjustment. Under the simulated conditions, the Cuk converter configuration demonstrated improved performance indicators. Future work will include economic analysis and the development of advanced ETAP models accounting for equipment aging and cyber-resilience. The simulation results suggest that connecting photovoltaic levels to a distribution grid may have a direct impact on reliability indices through load reduction. The influence of reactive power conditions on network operating performance was evaluated by reducing active and reactive power losses. The primary objective of this study was to enhance Diyala's power grid efficiency (132 KV). The proposed framework may support utility engineers to identify the optimal network reconfiguration strategy. Load flow analyses indicate that PV integration reduced total active power losses by approximately 37%. However, short-circuit studies demonstrate that PV integration creates substantial protection challenges by heavily increasing fault currents, illustrated by the surge from 7.459 kA to 34.335 kA at Bus 12.

These changes indicate that existing overcurrent relays must be adaptively coordinated to prevent system damage while maintaining grid stability. Furthermore, evaluating DC topologies revealed that Cuk converters demonstrated improved operating behavior compared to standard Boost configurations under fluctuating irradiance. A current limitation of this study is the absence of an economic analysis; future research should evaluate the system's overall costs alongside the typical 10 to 15-year payback period of PV investments. Future work should also focus on developing advanced ETAP reliability models that account for equipment aging, extreme weather resilience, and high-impedance fault detection strategies. Incorporating automated monitoring procedures implemented on programmable logic controllers (PLCs) will further enhance long-term system stability and maintenance optimization.

The contribution of this study lies in integrating reliability assessment with ETAP-based PV network analysis. This framework may be utilized by utility engineers to support network planning and reliability assessment activities. This technique can be extended to various power stations by implementing the indicated analytical approach to assess the reliability and efficiency of the photovoltaic system components. Future research directions include:

- **Develop Advanced Reliability Models:** research and propose more refined reliability models for ETAP to incorporate factors such as ageing equipment, weather effects, common mode failures, or cyber-attacks, which can impact the reliability of modern networks.
- **Sensitivity and Uncertainty Analysis:** Examine the sensitivity of ETAP reliability results to input data uncertainties (e.g., variation in failure rates, load forecasts). This can involve the application of Monte Carlo methods or other probabilistic techniques.
- **Network resilience assessment:** Beyond traditional reliability, researches can use ETAP to assess network resilience to extremes (natural disasters, attacks) and recommend strategy to improve resilience.
- **Reliability-based maintenance optimization:** use ETAP's reliability analysis capabilities to develop optimized predictive and preventive maintenance strategies by identifying critical components whose failure will have the greatest impact on overall system reliability.

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ETHICS STATEMENT

This study did not involve human or animal subjects and, therefore, did not require ethical approval.

STATEMENT OF CONFLICT OF INTERESTS

The authors declare no conflicts of interest related to this study.

LICENSING

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