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Power System Contingency Study of On-Grid Renewable Energy Resources with D.G. in a Different Conditions

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ABSTRACT

Contingency studies are conducted to assess the importance and reliability of power control systems by evaluating unspecified equipment outages under various conditions. This study conducts a comprehensive contingency analysis of a hybrid power system including distributed generators (D.G.s), wind farms, solar photovoltaic arrays, and grid connections to evaluate its resilience under N-1 power outage scenarios. Steady-state, dynamic, and voltage stability analyses are performed using Newton-Raphson and fast power flow simulations. The study presents key performance indicators for steady-state and dynamic responses, addressing voltage stability, thermal overload, and power flow redistribution. Mitigation strategies are proposed, including partial power compensation, ready-to-use generation scheduling, load shedding, and system resilience. The study also highlights the importance of contingency analysis based on reliable NERC/WECC standards and indicates how changing conditions impact grid resilience. The ETAP analysis supports an N-1 evaluation and the strategies used to determine system performance parameters, providing optimized operating thresholds for each component in the power system through the addition of user-defined components and failure scenarios. A hybrid power system was analyzed based on the separation of busbars, cables, distribution generator, transformers, wind generators, and the solar array. The study presents a new composite performance index (CPI) for use with hybrid power systems, integrating four sub-indices: voltage integrity (V/Vsp), real and reactive power deviations (ΔP and ΔQ), and branch overload (S/Ssp) to classify the severity of the contingency. The results show that the power outage on bus 1 (connected to the main grid) is the most severe (CPI = 103.065). In contrast, the outage's impact on the photovoltaic arrays is minimal (CPI < 1), highlighting the system's reliance on centralized generation. The study also shows that proximity to high-power transmission elements enhances the impact of the contingency, while distributed renewable energy sources enhance resilience. This work provides practical insights for grid operators managing hybrid systems amid increasing renewable energy deployment and climate-induced disruptions. A reliable power grid isn't just about avoiding blackouts, it's about designing systems that can adapt, recover, and keep electricity flowing even when things go wrong. This paper provides both the tools and the mindset needed to build that future.

Keywords:

Contingency analysis; N-1 criterion; power system stability; voltage violations; dynamic response; mitigation strategies.

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1. INTRODUCTION

The electrical grid includes various devices and equipment, generators, transformers, and other transmission lines. Any short circuit or malfunction in these instruments during operation could pose an environmental risk, potentially leading to system failure. This can be even more damaging to system management. A contingency is known as an unexpected outage. Therefore, it must be analyzed primarily to monitor conditions and report potential outages within the electrical system or related components. Safety limits must be included in the operating parameters. These constraints may be dynamic or restrictive, including capacity compliance, transients, and partial compliance limits. Exceeding these limits can lead to other major problems. Finally, comprehensive innovation has begun to address the most important elements for successfully formulating efficient new energy [1]. To prevent outages, the applied load must limit the flow in the lines within the grid [2]. LODF distribution factors (LODFs) are used for contingency analysis. In various contingency scenarios, to enhance the speed of LODFs, a simple matrix construction is used to transfer power elements [3]. Under normal operating conditions, power flow analysis produces data on voltage magnitudes and angles, active and reactive power flows at the relevant buses, and associated losses. To determine the maximum load factor, the power flow contingency is performed [4]. Contingency analysis is based on two categories of power system safety. First, Static Safety Assessment (SSA) primarily relies on voltage and transmission line stability. Second, the Dynamic Safety Assessment (DSA) examines the conditions in SSA, including dynamic and transient stability. Contingency analysis is performed using two common approaches: The classification method and the screening method. The classification method is a performance index (PI) technique that ranks contingency scenarios by relative severity. The screening method identifies the most damaging possibilities; however, in this case, the specified limits are breached. Due to the lengthy nature of contingency analysis, it is performed using an approximate power flow model [5].

Cascading failures or higher-order contingency occurrences frequently result in blackouts. The causes of these failures are [6]:

1. The concealed malfunction wherein electric current cannot be distributed to customers.
2. Inadequate protection of backup and deportation settings.
3. Switching the operation such that the system may respond the fault, however it may not rectify it.
4. Interference or discrepancies in communications that may not correlate with the circuit breaker's error identification.
5. The external factors contributing to the deterioration of the line owing to summer expansion.

This research presents a comprehensive and advanced analytical framework for contingency analysis in hybrid on-grid power systems that incorporate distributed generation sources, wind farms, and grid-connected solar systems. The novelty of this work lies in the introduction of a new composite performance index (CPI) that combines four sub-indices (voltage integrity, real and reactive power deviations, and branch overload) to accurately measure and quantify fault severity under various N-1 loss scenarios.

The research also employs steady-state and dynamic analyses using the Newton–Raphson method and Fast Power Flow using the ETAP environment, enabling the identification of optimal operational limits and the detection of system vulnerabilities. The applied contribution is the proposal of a set of smart mitigation strategies, including partial power compensation, backup generation scheduling, and load rationing, to enhance the grid's resilience and emergency response.

This work contributes to guiding power systems towards more efficient and sustainable design, relying on a combination of mathematical analysis and dynamic simulation to assess the reliability of hybrid systems in light of the increasing reliance on renewable energy.

2. LITERATURE SURVEY

Reactive power reservers and voltage stability of load buses are evaluated using V-Q curves. Both are obtained using the Newton-Raphson load flow approach [7]. Static analysis is a technique that uses commercial software to determine the post-contingency equilibrium state. The conditions required for pre-contingency and post-contingency load flow solutions are the same, but there is a significant difference between the two. Post-contingency load flow analysis fails to establish the exact equilibrium necessary for steady-state evaluation [8]. In the case of a branch outage, the Voltage Stability Index (VSI) can be evaluated by evaluating each line within the system and calculating line stability indices. The VSI evaluates the maximum potential load that can be connected to a bus to ensure stability before the system fails [9]. In recent years, contemporary distribution systems have relied on distributed energy resources (DERs) to meet the growing energy demand. DERs enhance energy efficiency and reliability. Islanding occurs when distributed generators supply power to a specific location even when disconnected from the grid. There are two categories of islanding: cross-islanding and purposeful islanding. The voltage and frequency on the cross-island are regulated independently of the DER equipment connections. In the specific case of islanding, the system is precisely designed to address these conditions [10]. Interruptions in a distributed power generation system cause changes in frequency and voltage. This can be corrected by modeling distributed generators using the common loop of an automatic voltage regulator (AVR) and automatic generation control (AGC). Stability can be achieved via the islanding technique for many types of contingencies [11]. Several researchers have sought to improve this method. The contingency classification of the PI is performed using AC power flow and distribution variables for different bus systems. This provides improved stability and accuracy compared to the standard performance index [12]. The 10-bus system is used for contingency classification, which compares the exact classification approach with the fine classification method. It is based on a practical approach. The fine classification approach is compatible with the classification methodology. It is a rapid methodology applicable to complex power system networks [13]. For N-1 contingency classification, the existing power grid system is essential. Distribution factors are used to quantify line flows. This is achieved through phase measurements that also predict the system sensitivity. The total active and total power equations are expressed in polynomial form. Contingency classification is performed based on the total line summary and the total voltage performance index. The least-squares curve fitting method analyzes a random set of points to fit them to the specified constraints. The value of this method lies in its independence from repeated power flow calculations, thus eliminating complex line flows. The only limitation of this system is that each load bus requires voltage differentiation. A long time is required to collect system data [14]. Contingency assessment can also be performed with respect to line stability. An online real-time evaluation method is used, using a balanced solution to determine the line stability index. This stabilizes the voltage boundary. A balanced solution region is created by formulating the active and reactive power equations. The power is analyzed, and the similarities and differences between the solutions are evaluated. This solution requires fewer real-time steps and can ensure robust voltage stability in the grid system [15]. Another real-time evaluation method is implemented by redefining the contingency. This approach calculates the number of fractions required to isolate the system containing any potential outage. Contingency assessments are prioritized by activating circuit breakers [16]. Another method for determining real-time contingency analysis involves transmission switching. This system faces some limitations, including the feasibility of AC load flow, complexity, and the ability to manage large-scale power networks. The necessary switching is accomplished through three practical methods in conjunction with parallel computing. These algorithms provide rapid results [17]. A time-domain simulation method is used to determine N-K probabilities. The system initially identifies a list of simple probabilities and then moves on to more severe conditions. The simulation results are displayed with each possible classification. If the interaction is unstable, A contingency plan is developed. It is also evaluated based on N-(K+1). This technique has been applied to IEEE Nordic and has been shown to detect two N-2 contingencies simultaneously [18]. A combined performance index (CPI) was calculated based on four sub-indices: the bus voltage safety index (PIV/Vsp), the actual power flow index (PIΔP), the reactive power flow index (PIΔQ), and the branch overload safety index (PIS/Ssp).

The results showed that the Mangombe-Oyomabang line outage (Scenario 22) was the most severe, with the load flow failing to reach convergence, followed by the Oyomabang-Nguosu 1 line outage (Scenario 36), with combined performance indices of 992.6191 and 79.74415, respectively.

Other scenarios also showed overloaded lines and transformers, high power losses, and low or high bus voltages, indicating the system's sensitivity to certain transmission line outages [19]. Machine learning (ML) techniques were used to predict the outcomes of emergency analyses by identifying performance indicators (PIs) under rapidly changing, dynamic operating conditions. Supervised learning methods based on Decision Tree (DT), Random Forest (RF), and Extra Tree (ET) were used to predict the results of the emergency analysis and evaluate the accuracy of each model. A quantitative comparison was conducted among these models to determine the most efficient and accurate method for predicting the electrical system's behavior during an emergency. In addition, modal analysis was employed to determine the optimal location of the STATCOM device to improve voltage stability and enhance the dynamic system response [20]. A framework based on CA to assess the simultaneous effect of large-scale solar photovoltaic (PV) power plants integrated with the existing power grid, particularly, in the aspects of implementing effective measuring indices. Simulation studies have been carried out on a practical power system modelled to account for the probability of solar irradiance at different locations in Sarawak. This study can provide insight into identifying the level of insecurity for a large-scale deployment of solar PV systems in Sarawak [21].

3. SIGNIFICANCE OF THE WORK

This research enhances the reliability and stability of hybrid power systems by developing an integrated N-1 Contingency Analysis framework that encompasses distributed generation systems, wind farms, solar panels, and connections to the national grid.

The research also presents a new Composite Performance Index (CPI) that integrates four sub-indices: voltage integrity (V/Vsp), actual and reactive power deviations (ΔP and ΔQ), and branch overload (S/Ssp), to quantitatively classify the severity of each emergency.

The research demonstrates the potential of steady-state and dynamic analyses in ETAP to identify system vulnerabilities and optimize operating limits via user-defined failure scenarios.

The research also proposes mitigation strategies, including partial power compensation, backup generation scheduling, and load optimization, to enhance the grid's flexibility and sustainability.

Thus, this work provides a methodological framework and practical results that help grid operators design hybrid electricity systems that are more resilient to operational changes and to increased reliance on renewable energy sources.

4. CONTINGENCY

Analysis of contingency is important for assessing the impact of power outages on the safety of power systems during operational and pre-planning periods. It conducts the necessary investigations, Assesses, sorts, and prioritizes impacts on power systems when disturbances or unplanned outages occur.

4.1. Contingency status for one outage (N-1)

The criterion N-1 pertains to interruptions caused by any of the following unforeseen events:

1. The internal overhead line is operated, through which the load beams are equipped via an antenna line or a single cable.
2. There is an outage of an individual transformer, excluding those that connect loads via a transformer single radial.
3. A generator has been lost, regardless of whether it is grid-connected or embedded.
4. There is a deficiency of shunt devices, including capacitors and reactors.

The N-1 requirement is fulfilled if, after the failure of a single system component (e.g., transmission line, transformer, generating unit, etc.), the ensuing regulations are adhered to:

a.No violation of the threshold values for network operational variables (i.e., operational voltage, frequency) exists that could jeopardize the security of the power system or result in excessive stress on equipment, damage, destruction, or an intolerable reduction in equipment lifespan.

b.No equipment or loading of the transmission line has surpassed 100% of its operational thermal limit capacity.

c.Supply disruption is prevented

4.2. Contingency (N-K)

N is the quantity of a specific element, whereas K signifies the corresponding contingency imposed on the power system network, where K = 0, 1, 2, …, N. When K = 0, it indicates that the system is in a healthy state. It is often referred to as a pre-contingency state. If K = 1, it means that only one element is out of service. It is often referred to as the N-1 criterion. The N-1 criterion is an abstraction denoting the equivalence of a singular situation. It results in the tripping of one element due to a three-phase short circuit fault. The challenge in studying N-K situations stems from the complexity of their combinations. The quantity of contingencies may fluctuate based on the analytical level, various elements (N), and the degree of contingency.

The first level contingency pertains to N-1, the second level contingency pertains to N-2, and so forth. Traditionally, the system's dynamic security analysis is performed for a brief period in response to predetermined contingencies. In several instances, the perilous consequences of contingencies may be readily overlooked until they manifest, as the probability of their occurrence is significantly lower. Nonetheless, other scenarios will arise, and the ramifications may be significant for the analysis of high-risk N-k contingencies in online secure operational assessments.

5. SIGNIFICANCE OF THIS WORK

This paper is of great importance because it ensures the stability, safety, and efficiency of power systems under normal and contingency conditions, especially when renewable energy sources are added. By studying contingency situations under different operational and environmental scenarios, public utilities can prevent catastrophic failures, improve grid performance, and enhance their resilience to future challenges, such as renewable energy fluctuations and climate change. This paper presents a contingency analysis of a hybrid system transmission network, examining and evaluating the impact of outages of transmission, cable, distribution generator, transformer, wind generator, and solar system components on its operational status using a composite performance index (CPI). The Fast-Decoupled method load flow was used to analyze voltage imbalance across various transmission processes and to calculate the CPI. The research used the ETAP software as a tool to study, simulate, and analyze the hybrid system.

6. PROPOSED METHODOLOGY

Figure 1 illustrates a flowchart of the methodology used in this study, which aims to evaluate power grid outages under different conditions.

In this research, the impact of N-1 contingency on the system performance index was evaluated, and the results were compared with the safe operating limits of each component in the power system based on specific outage and failure scenarios. To obtain accurate results, the AC load flow feature is activated for each emergency.

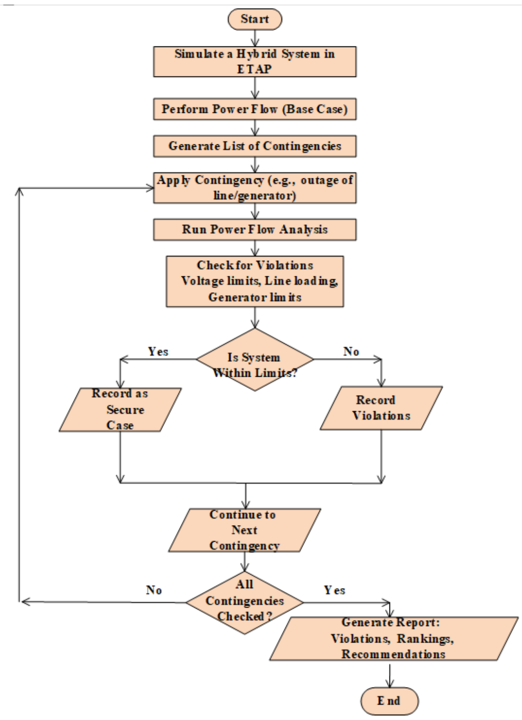


Fig.1 Flowchart of the proposed Method.

The main steps include:

6.1. Load Flow Using ETAP

The load flow analysis module in ETAP was used to calculate main grid voltage, substation power factors, currents, and power flows across various electrical grid components. The program supports a variety of energy sources and offers flexibility in interconnecting multiple types of power grids, including motors and generators of all types [22][23].

One of the most notable advantages of ETAP is its ability to perform accurate mathematical analyses of both loop and radial systems, making it an effective tool for evaluating the performance of electrical grids under various operating conditions. ETAP offers three main methods for calculating load flow [23]:

1-Adaptive Newton-Raphson (NWR)
2-Classical Newton-Raphson (NWR)
3-Fast Decoupled Load Flow (FDLF)

These methods have different rates of convergence, and one may be more appropriate than the other depending on the characteristics of the system under study.

The Newton-Raphson method is derived from the Fast-Decoupled method. This method assumes that a small change in the bus voltage does not significantly alter the actual power at that voltage. Similarly, reactive power does not change considerably with a small change in the bus voltage phase angle. Thus, the load flow equation used in the Newton-Raphson method can be simplified into two sets of equations, which can be solved iteratively.

The contingency analysis study uses the Fast-Decoupled method to calculate load flow. The AC load flow analysis is performed first in the base case, and then, in each outage case, the disconnected elements are excluded and another type of load flow, called the contingency load flow, is performed. Based on this outage, the bus voltage and branch load may be significantly affected. The contingency load flow can be determined by decreases in bus voltage and increases in branch load.

6.2. ETAP Contingency Calculation

In the ETAP Contingency Analysis, a single method is used for load flow calculation: the AC load flow is initially run for the base scenario. Subsequently, for each outage, the affected items are excluded, and an additional load flow analysis is conducted, referred to as contingency load flow.

The outage can substantially impact bus voltage and branch loading. Contingency load flow can identify buses with undervoltage and branches with overload. In this paper, the Electrical Transient Analyzer Program (ETAP) was used to simulate the Hybrid System network, as shown in Fig. 2.

6.3. Contingency Scenarios Using ETAP

ETAP's Contingency Analysis module evaluates the impact of N-1 and N-2 contingencies, determines system performance indicators, and compares these results with the safe operating limits of each power system component, accounting for outages and faults that may occur. ETAP's user-friendly interface allows running essential and emergency load flows to evaluate the impact of an outage on the low-voltage (OLV).

In this study, N-1 Contingencies were used for different scenarios: (bus outage, transformer outage, D.G. outage, cables outage, wind generators outage, and PVs outage)

In these scenarios, parts of the network will be disabled individually, separating both Buses, Transformers, D.G., Cables, wind generators, and PVs. After that, each case will be discussed separately, followed by a comprehensive comparison of all the studied cases.

The performance index is used to classify outage cases in the system, as it reflects the severity and impact of the interruption.

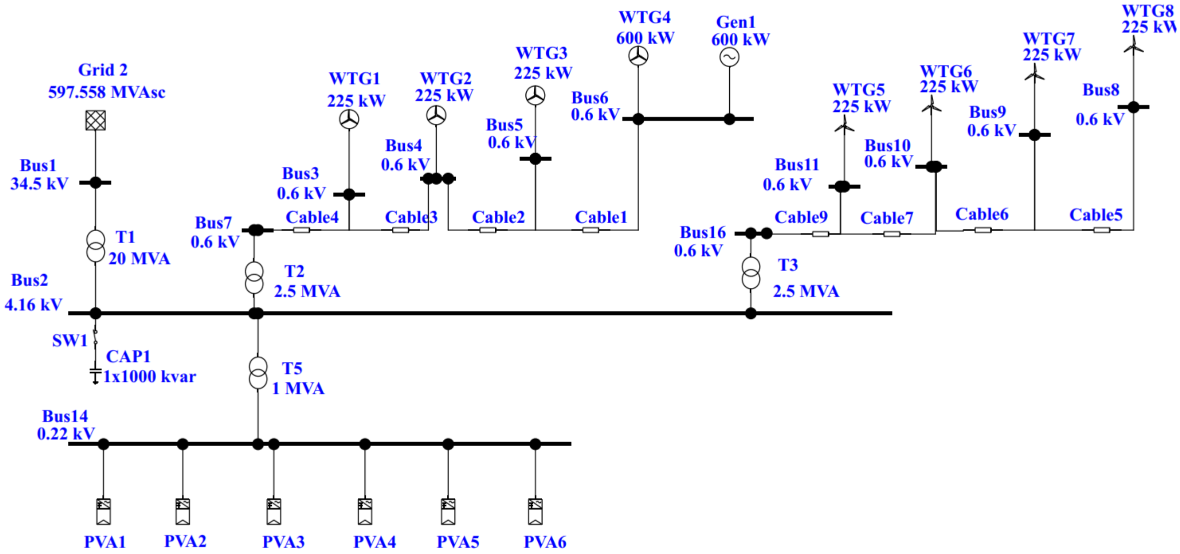


Fig.2 Hybrid Proposed Network.

6.4. Performance Index

A performance index is utilized to categorize outages. The indicator may reflect the severity of the outage. The index of performance is a numerical value and lacks a unit of measurement. Consequently, we can incorporate many indications and assign weights [19][23].

6.4.1 V/Vsp (Voltage Security Performance Index): The security voltage is calculated based on the difference between the bus's voltage before and after the contingency. This indicator reflects the stability of network voltages under contingencies, such as losing one of the elements (bus, transformer, or generator). The smaller the indicator value, the smaller the change in bus voltage, and therefore the system maintains its stability better. The greatest values indicate larger voltage differences, which means a deterioration in the safety and stability of the voltage. The voltage bus security index is determined by the difference in voltage at the bus before and after the potential change. Lower values signify lesser disparities.

$$P_{IV/Vsp} = \left[\sum_{n-1}^{N}\left(\left(V_{n\_PostCon} - \mathrm{V}_{\mathrm{n\_Spec}}\right)/V_{Limit}\right)^2\right]/N \quad \ldots(1)$$

where:

$\mathrm{P}_{\mathrm{IV\,/\,Vsp}}$ for the instruments Rating

$V_{n\_PostCon}$ After the contingency voltage bus in percentage value.

$\mathrm{V}_{\mathrm{n\_Spec}}$ Specified bus voltage base in percentage value, 100% in this case.

V_{Limit} Limit for voltage bus critical alert. $V_{Limit} = |V_{critical} - 100\%|$

N Buses number in the system.

$\mathrm{P}_{\mathrm{IV\,/\,Vsp}}$ for the Base Case

$V_{n\_PostCon}$ After the contingency voltage bus in percentage value.

$\mathrm{V}_{\mathrm{n\_Spec}}$ Specified voltage bus base in percentage value, base case in this case.

V_{Limit} Limit for voltage bus critical alert. $V_{Limit} = V_{Crit\_Dev}$, which Alert critical voltage deviation as a percentage. V_{Crit_Dev} is collected from the Alert page.

6.4.2 ΔP (Reactive Power Flow Change Index): This indicator was calculated to measure the extent of the reactive power flow in the network due to a contingency (such as a bus separation or a malfunction in one of the components). The indicator depends on the difference between the reactive power flow before and after the contingency. The decrease in the indicator's value suggests a slight change in the flow of power, indicating greater flexibility and stability in the system. In contrast, high values reflect a significant change in flows, which may indicate a critical state or instability in the system.

$$PI_{\Delta P} = \left[\sum_{n-1}^{N}\left(\left(P_{n\_PostCon} - \mathrm{P}_{\mathrm{n\_Base}}\right)/\mathrm{P}_{\mathrm{n\_Base}}\right)^2\right]/N \quad \ldots(2)$$

$P_{n\_PostCon}$ Branch-n after contingency reactive power flow

$\mathrm{P}_{\mathrm{n\_Base}}$ Branch-n base case reactive power flow.

N branches Number changes in the system with reactive power flow.

6.4.3 ΔQ (Reactive Power Flow Change Index): This indicator is used to assess the extent of change in the interactive power flow in the buses due to the occurrence of a contingency, such as the loss of one of the elements in the network. The indicator is calculated based on the difference between the real power flows before and after the contingency. Small values of the index indicate slight changes in the flow of reactive power, indicating the system's ability to adapt and maintain stability. As for the large values, they reflect noticeable changes that may indicate weakness in the system's elasticity or its approach to safe operating limits.

The reactive power flow variability index is determined by the difference in reactive power flow before and after the Contingency. Lower values signify lesser disparities.

$$PI_{\Delta Q} = \left[\sum_{n-1}^{N}\left(\left(Q_{n\_PostCon} - \mathrm{Q}_{\mathrm{n\_Base}}\right)/\mathrm{Q}_{\mathrm{n\_Base}}\right)^{2}\right]/N \quad \ldots(3)$$

$Q_{n\_PostCon}$ Branch-n after contingency reactive power flow.

$\mathrm{Q}_{\mathrm{n\_Base}}$ Branch-n base case reactive power flow.

N Branches number changes in the system with reactive power flow.

Table 1: Bus Input Data

Bus ID	Kv	Generation	
		MW	Mvar
Bus 1	34.500		
Bus 2	4.160		
Bus 3	0.600	0.230	
Bus 4	0.600	0.230	
Bus 5	0.600	0.230	0.139
Bus 6	0.600	1.200	0.744
Bus 7	0.600		
Bus 8	0.600	0.225	0
Bus 9	0.600	0.225	0
Bus 10	0.600	0.225	0
Bus 11	0.600	0.225	0
Bus 12	0.600		
Bus 14	0.22	0.018	0.003
Bus 1	34.500		

Table 2: Line/Cable/Busway Input Data

Bus ID	Size	R	X
Cable1	400	0.056700	0.074800
Cable 2	400	0.056700	0.074800
Cable 3	400	0.056700	0.074800
Cable 4	400	0.056700	0.074800
Cable 5	95	0.229700	0.077400
Cable 6	95	0.229700	0.077400
Cable 7	400	0.056700	0.074800
Cable 8	400	0.056700	0.074800

Table 3: Two-Winding Transformer Input Data

Bus ID	Primary Kv	Secondary Kv	MVA
T1	34.500	4.160	20
T 2	0.600	4.160	2.5
T 3	0.600	4.160	2.5
T 5	4.160	0.222	1

6.4.4 S/Ssp (Overloading Security Index): This indicator measures the extent to which network branches (such as transmission lines or transformers) are overloaded after a specific network contingency. The index depends on the download rate for each branch relative to its maximum permitted rate. Small values of the index indicate fewer violations of the loading limits, and thus a safer operating position. As for the greatest values, they indicate branches operating beyond their limits, which may pose technical risks and outages.

The branch overload condition determines the branch overload security index. Lower values indicate fewer overload violations.

$$PI_{S/Ssp} = \left[\sum_{n-1}^{N}\left(S_{n\_PostCon}/S_{Limit}\right)^{2}\right]/N \quad \ldots(4)$$

where:

$\mathrm{PI}_{\mathrm{S\,/\,Ssp}}$ for the instruments Rating

$S_{n\_PostCon}$ Branch-n after contingency branch load flow, MVA for transformers and Amps for other branches.

S_{Limit} Branch overloading limit, in this case $S_{Limit} = Ampacity * \mathrm{S}_{\mathrm{Crit\_Alert}}$

N Branches Number in the system. For PIS / Ssp based on Base Case

$S_{n\_PostCon}$ Branch-n after contingency load flow branch, MVA for transformers, and Amps for other branches.

S_{Limit} Branch overloading limit, in this case $S_{Limit} = S_{Base} * (1 + S_{Crit\_Dev})$.

N Branches number in the system.

6.4.5 COMPINED (Composite Performance Index – CPI): The summation of the performance indices is used to assess the overall condition of the system after a contingency case by summing the balanced partial indicators, namely (V/V_{sp}, ΔP ,ΔQ , S/S_{sp}).

$$CPI = \sum[\mathrm{V/Vsp}, \Delta\mathrm{P}, \Delta\mathrm{Q}, S/Ssp] \quad \ldots(5)$$

The network was simulated using the ETAP program, as shown in Fig. 2. The network consisted of a Distribution Generator, Transformers, wind turbines, a PV system, and the Grid. The network parameters were as listed in Tables 1, 2, and 3 [24].

7. RESULTS AND DISCUSSIONS

7.1. Load Flow Results

In this study, the Fast-Decoupled (F.D.) method is derived from the Newton-Raphson (N.R.) method. Therefore, the Newton-Raphson load flow equation can be reduced to two independent sets of load flow equations, each of which is solved iteratively.

$$[\Delta P] = [J_1][\Delta \delta] \qquad \ldots(6)$$

$$[\Delta Q] = [J_4][\Delta V] \qquad \ldots(7)$$

The Fast-Decoupled method reduces computer memory requirements by about half compared to the Newton–Raphson (N.R) method and allows the load flow equations to be solved much more quickly, due to the stability of the Jacobian matrices. The convergence criteria for the Fast-Decoupled method, like those for the Newton-Raphson method, are based on the mismatch between real and reactive power, which is typically within 0.001 per MW and per MVAR. Although it is not as accurate as the Newton-Raphson method for a fixed number of iterations, the time savings and more convenient convergence criteria make it perform well. The Fast-Decoupled method is a suitable alternative to the Newton-Raphson method and is recommended when the latter fails, especially when analyzing extended radial power systems or transmission networks that include long lines or cables. The Fast-Decoupled method was used due to its ability to address convergence problems that other methods may encounter, as shown at Fig. 3 and Table 4. This method relies on small-step iteration techniques when there is a risk of divergence, enhancing the program's ability to find accurate solutions even in complex systems.

7.2. Contingency Scenarios Results:

A. Buses Outage: In this scenario, all buses in the network are individually disabled, while the rest of the system components remain operational. After each separation case, the performance indicators are calculated, and the results are recorded separately for each case to assess the impact of each bus on the system's stability and safety, as shown in Fig. 4 and Table 5.

By collecting and analyzing data indicators, it can be noted that the compound performance index (CPI) provides a comprehensive and pre -evaluating evaluation of potential contingency situations that the network may face. When arranging the results of the complex performance index in descending order (from top to bottom), cases can be classified by their risk and impact on the system's stability and safety.

The higher values of the index indicate more serious and effective contingency situations, as shown in Table 5. Bus 1 outage is the most dangerous contingency case due to its association with the high-power grid, while smaller values reflect fewer effective cases. In this way, the arrangement of the complex indicator can serve as a tool to determine processing and contingency planning priorities by identifying the scenarios that require urgent intervention.

Table 4 Line/Cable/Busway Input Data

Bus ID		Voltage		Load Flow			
From	To	% Mag	Ang	MW	Mvar	Amp	% PF
Bus 1	Bus 2	100	0	-2.676	-0.032	44.8	100
Bus 2	Bus 1	100.08	0.6	2.678	0.061	371.5	100
Bus 2	Bus 7	--	--	-1.78	0.904	276.8	-89.2
Bus 2	Bus 12	--	--	-0.88	0.034	122.2	-99.9
Bus 2	Bus 14	--	--	-0.018	0.003	2.6	-98.3
Bus 3	Bus 4	99.251	4.6	-1.595	0.868	1760.3	-87.8
Bus 3	Bus 7			1.824	-0.768	1919.0	-92.2
Bus 4	Bus 5	99.636	6.1	-1.392	0.933	1618.2	-83.0
Bus 4	Bus 3	--	--	1.621	-0.833	1760.3	-88.9
Bus 5	Bus 6	99.786	7.3	-1.184	0.765	1359.3	-84.0
Bus 5	Bus 4	--	--	1.414	-0.904	1618.2	-84.2
Bus 6	Bus 5	99.942	8.4	1.2	-0.744	1359.3	-85.0
Bus 7	Bus 3	98.640	3.2	-1.793	0.809	1919.0	-91.1
Bus 7	Bus 2	--	--	1.793	0.809	1919.0	-91.1
Bus 8	Bus 9	103.600	3.1	0.225	0.000	209.0	100
Bus 9	Bus 8	102.908	3	-0.223	0.001	209.0	100
Bus 9	Bus 10	--	--	-0.448	-0.001	419.4	100
Bus 10	Bus 9	101.519	2.7	-0.442	0.003	419.4	100
Bus 10	Bus 11	--	--	0.667	-0.003	632.6	100
Bus 11	Bus 10	101.006	2.3	-0.667	0.007	632.6	100
Bus 11	Bus 12	--	--	0.889	-0.007	847.0	100
Bus 12	Bus 11	100.325	1.8	-0.883	0.015	847.0	-100
Bus 12	Bus 2	--	--	0.883	-0.015	847.0	-100
Bus 14	Bus 2	100.086	0.7	0.018	-0.003	48.7	-98.3

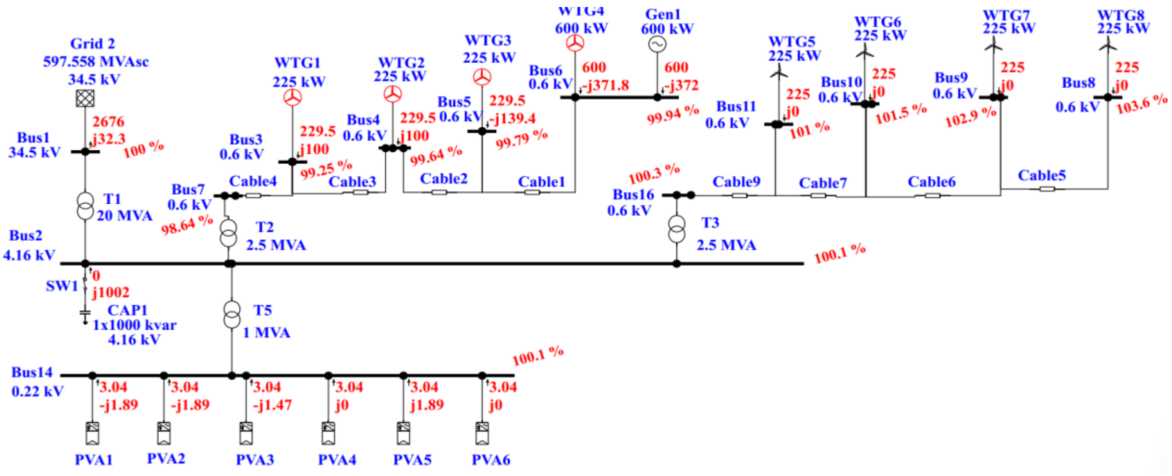


Fig. 3 Load Flow of Network

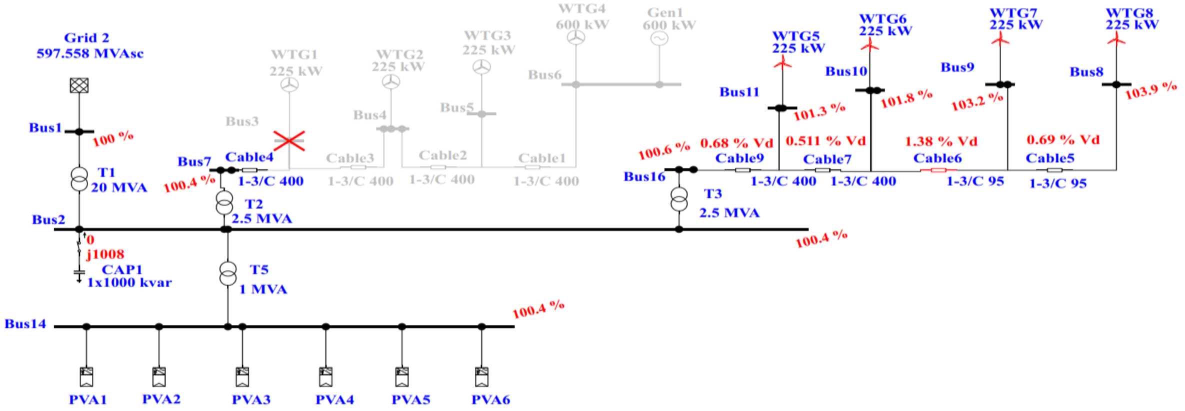


Fig. 4 Bus 3 outage of the network

B. Cables Outage: In this scenario, all cables in the network are individually disabled, while the rest of the system components remain operational. After each separation case, the performance indicators for system security and stability are calculated, and the results are recorded separately for each case. This analysis aims to assess the effect of each cable on the system's stability and safety by comparing performance indicators after each separation. The results of this scenario, shown in Figure 5 and Table 6, explain how the effect of each cable-separation case is displayed on the compound indicator, which helps identify the most influential factor on the system's stability.

Table 5 Contingency Data for Bus Outages

Outage Device ID	V/V_{sp}	ΔP	ΔQ	S/S_{sp}	COMPINED (CPI)
Bus 1	101.0654	1	1	0	103.0654
Bus 2	93.37309	1	1	1.92E-16	95.37309
Bus 3	30.55976	0.90691	38.13381	0.428231	70.02871
Bus 4	22.98239	0.810048	30.10895	0.433347	54.33474
Bus 5	15.34554	0.682871	22.69321	Undefined	38.72162
Bus 6	7.685366	0.526412	16.02752	Undefined	24.2393
Bus 7	38.0419	0.90691	38.1338	0.428233	77.51084
Bus 8	8.257209	0.246839	0.433046	0.59957	9.536664
Bus 9	16.403	0.492082	0.723119	0.50514	18.12334
Bus 10	24.33054	0.695636	0.850666	0.461503	26.33834
Bus 11	32.17809	0.851343	0.883365	0.444364	34.35716
Bus 12	39.92035	0.851343	0.883362	0.444364	42.09942
Bus 14	7.705612	1	0.50159	0.756634	9.963836

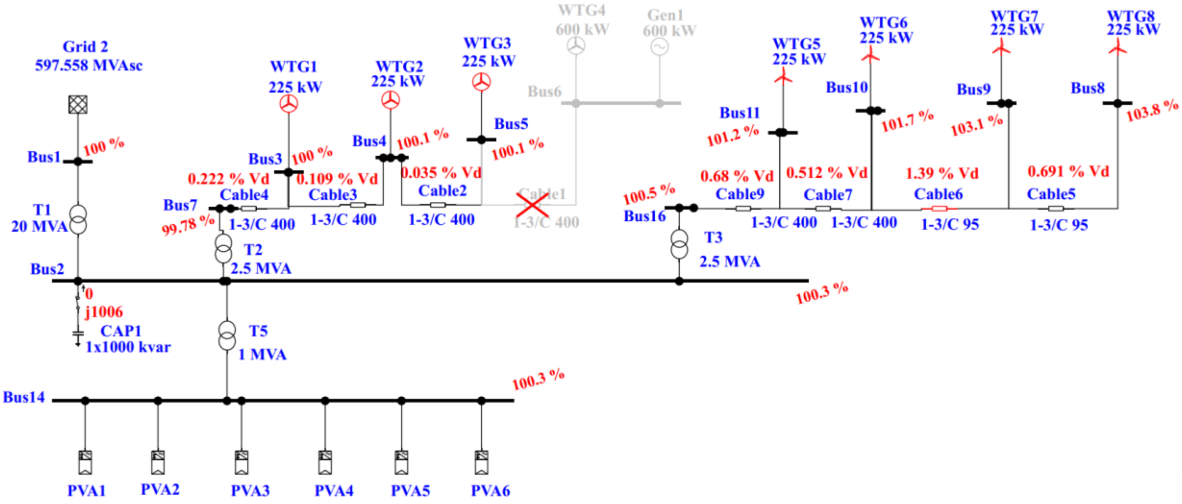


Fig. 5 Cable 1 outage of the network

Table 6 Contingency Data for Cables Outage

Outage Device ID	VV_{sp}	ΔP	ΔQ	SS_{sp}	COMPINED (CPI)
Cable 1	7.685366	0.526412	16.02752	Undefined	24.2393
Cable 2	15.34554	0.682871	22.69321	Undefined	38.72162
Cable 3	22.98239	0.810048	30.10895	0.433347	54.33474
Cable 4	30.55976	0.90691	38.13381	0.428231	70.02871
Cable 5	8.257209	0.246839	0.433046	0.59957	9.536664
Cable 6	16.403	0.492082	0.723119	0.50514	18.12334
Cable 7	24.33054	0.695636	0.850666	0.461503	26.33834
Cable 8	32.17809	0.851343	0.883365	0.444364	34.35716

By collecting and analyzing performance indicators, the CPI provides a comprehensive, early evaluation of potential Contingency situations the network may face. When arranging the results of the complex index in descending order (from top to bottom), contingency situations can be classified by their seriousness and impact on the system's stability and safety.

The higher values of the index indicate more serious and effective contingency situations, as shown in Table 6, where it turns out that the interruption of the Cable 4 represents the most serious situation on the network, due to its critical location and its proximity to grid or the main contract in the system. On the other hand, the smaller values indicate a lesser effect on network performance.

Consequently, the arrangement of the compound performance index can be relied upon as an effective tool for determining priorities in dealing with contingencies, by highlighting scenarios that require urgent intervention and proactive plans to enhance the reliability and safety of the network.

C. Distributed Generator (D.G.) Outage: In this scenario, the D.G. in the network was separated while the rest of the system components remained operational. After implementing the separation process, the performance indicators of the security and stability of the system were calculated, and the results were recorded.

This analysis aims to assess the impact of the D.G. on the stability and safety of the network, by comparing performance indicators before and after the separation. The results of this scenario, shown in Figure 6 and Table 7, indicate the effect of the D.G. loss on the compound performance index (CPI).

By collecting and analyzing performance indicators, the Performance Index provides a comprehensive, early assessment of potential contingencies the electrical grid may face when a distribution generator is disconnected.

Table 7 Contingency Data for Distributed Generator (D.G.) Outage

Outage Device ID	V/V_{sp}	ΔP	ΔQ	S/S_{sp}	COMPINED (CPI)
G 1	0.000909	0.128843	5.361094	0.592986	6.083831

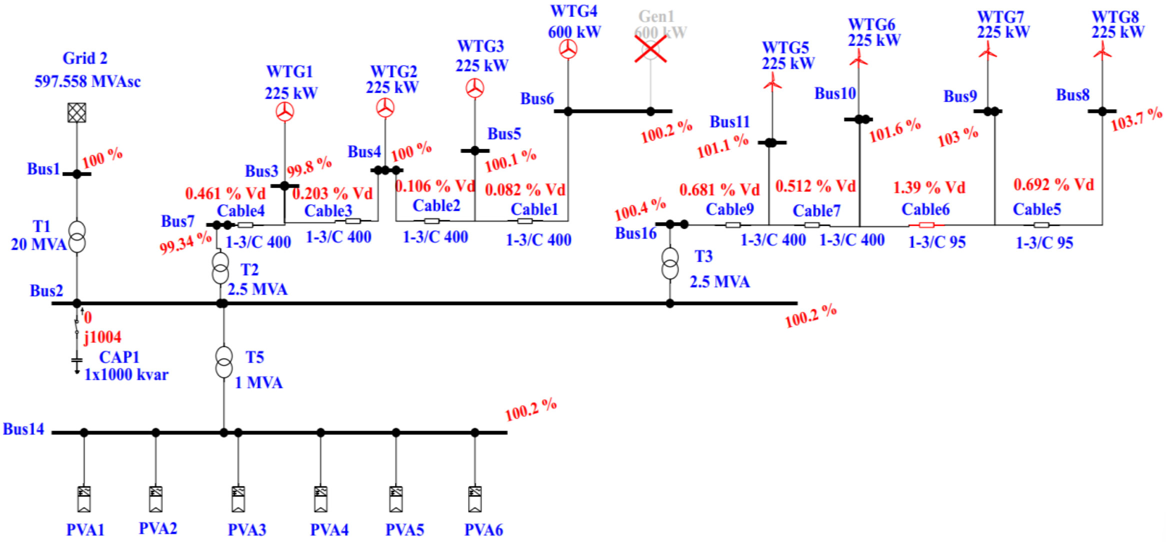


Fig. 6 D.G. outage of the network

D. Photovoltaic Solar Panel (PSV) Outage: In this scenario, all the Photovoltaic Solar Panel in the network were separated individually, where each cell is disabled separately, while maintaining the operation of the rest of the system components. After each separation process, the performance indicators associated with the security and stability of the system are calculated, and the results are recorded separately for each case.

This analysis aims to assess the extent of the effect of each Photovoltaic Solar Panel on the stability and integrity of the network, by comparing performance indicators before and after the separation. The results of this scenario are shown in Figure 7 and Table 8, where the effect of each of the Photovoltaic Solar Panel separation is clarified on the compound performance index (CPI).

This analysis helps in determining the most sensitive and influencing Photovoltaic Solar Panel locations, which contributes to making better decisions regarding the distribution of renewable energy sources and planning protection and strengthening procedures.

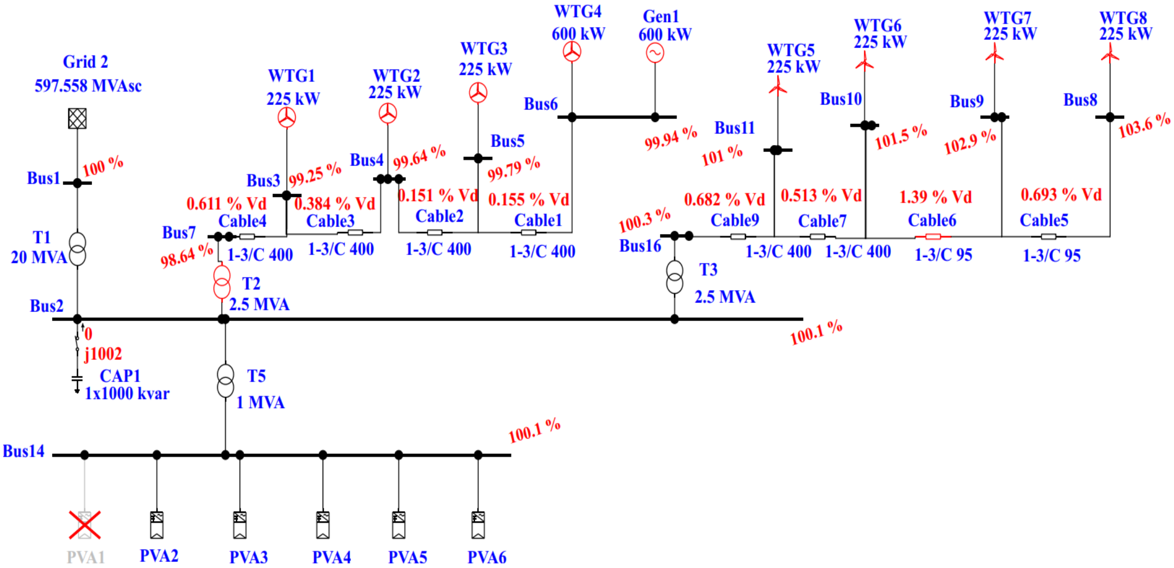


Fig. 7 PV outage of the network

Table 8 Contingency Data for PVA outage

Outage Device ID	VV_{sp}	ΔP	ΔQ	SS_{sp}	COMPINED (CPI)
PVA1	4.63E-08	0.027778	0.157363	0.804109	0.98925
PVA2	4.63E-08	0.027778	0.157363	0.804109	0.98925
PVA3	2.33E-08	0.027778	0.096251	0.804387	0.928416
PVA4	5.39E-09	0.027778	0	0.805939	0.833717
PVA5	1.3E-07	0.027778	0.15576	0.809198	0.992737
PVA6	5.39E-09	0.027778	0	0.805939	0.833717

Higher index values indicate more serious and effective cases, as shown in Table 8. Despite the values of some scenarios, the results showed that the outage of PVA 5 represents the most dangerous possible contingency, due to its critical location and its proximity to the load center or one of the main contracts in the network. In contrast, the smaller values indicate a limited effect on the network's performance and stability.

E. Wind Turbine Outage: In this scenario, all wind turbines in the grid were individually disconnected, with each turbine disabled while the rest of the system components continued to operate. After each disconnection, performance indicators related to grid security and stability were calculated, and the results for each case were recorded. This analysis aims to assess the impact of each wind turbine on the electrical system's stability by comparing performance indicators before and after disconnection. The results of this scenario are presented in Figure 8 and Table 9, where the impact of each case on the Composite Performance Index (CPI) is clearly visible.

This methodology helps identify the most sensitive and impactful wind turbine locations, supporting renewable energy distribution decisions and the development of protection and reinforcement strategies.

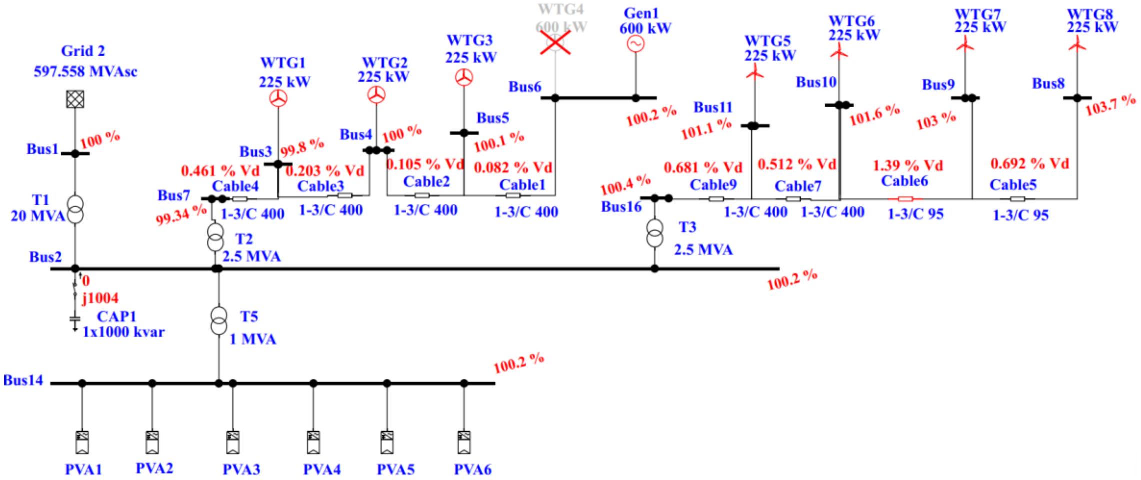


Fig. 8 WTG outage of the network

Table 9 Contingency Data for WTG outage

Outage Device ID	VV_{sp}	ΔP	ΔQ	SS_{sp}	COMPINED (CPI)
WTG 1	0.001227708	0.0129157	0.6073784	0.7977068	1.419228608
WTG 2	0.00208334	0.01440796	0.4044612	0.7881321	1.2090846
WTG 3	0.000541512	0.01569171	1.798737	0.7431953	2.558165522
WTG 4	0.000908371	0.1288436	5.361066	0.592993	6.083810971
WTG 5	0.000159724	0.0447759	0.07009713	0.7559052	0.870937954
WTG 6	0.000380261	0.06144379	0.1278385	0.718151	0.907813551
WTG 7	0.001870482	0.09752639	0.1979393	0.6690103	0.966346472
WTG 8	0.003335248	0.2467801	0.4329345	0.5995764	1.282626248

F. Transformer Outage: In this scenario, all transformers in the network were disconnected individually, with each transformer disabled, while the rest of the system components continued to operate unchanged. After each disconnection, performance indicators related to network security and stability were calculated, and the results for each case were documented. This analysis aims to evaluate the impact of each transformer on the electrical system's stability by comparing performance indicators before and after disconnection. The results of this scenario are presented in Figure 9 and Table 10, where the impact of each case on the Composite Performance Index (CPI) is clearly visible.

This methodology highlights the importance of identifying transformer locations with the greatest impact on network stability, thereby enhancing transformer distribution decisions and planning protection and reinforcement strategies.

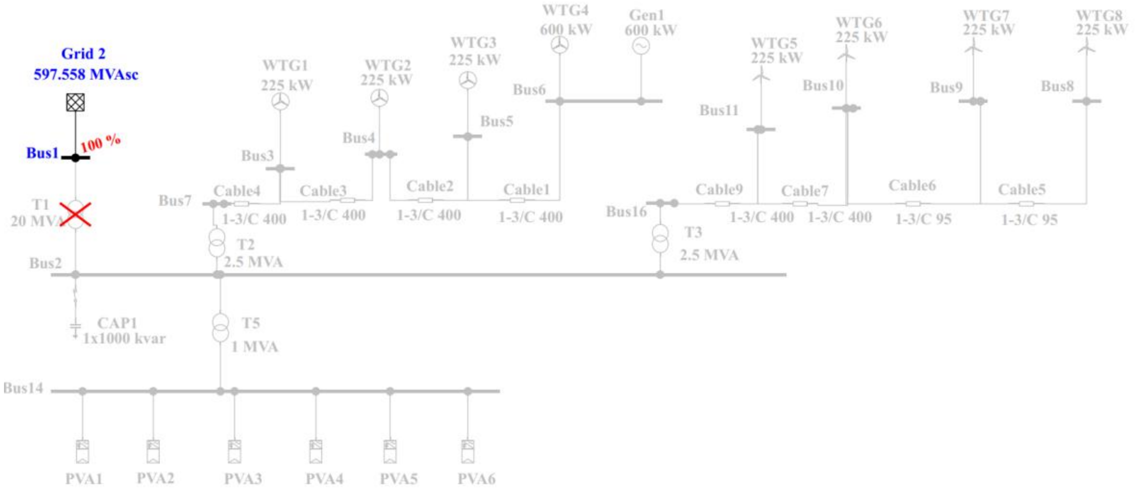


Fig. 9 Transformer outage of the network

Table 10 Contingency Data for Transformer Outage

Outage Device ID	VV_{sp}	ΔP	ΔQ	SS_{sp}	COMPINED (CPI)
T1	93.37309	1	1	1.92283E-16	95.37309
T 2	38.0419	0.9069104	38.1338	0.4282326	77.510843
T 3	39.92035	0.8513429	0.8833623	0.444364	42.0994192
T 4	7.705612	1	0.5015899	0.7566341	9.963836
T 5	93.37309	1	1	1.92283E-16	95.37309

Higher CPI values indicate more severe and impactful scenarios, while lower values reflect a limited impact on the network. The results showed that disconnecting T1 is the most severe contingency due to its critical location and proximity to the main power point. Its disruption leads to a complete power outage and the shutdown of the entire system. The remaining cases, however, exhibited less pronounced effects on the network's overall performance.

Accordingly, the arrangement of the compound performance index can be relied upon as an effective tool for determining priorities in dealing with contingency situations, highlighting the scenarios that require urgent intervention, and for developing proactive plans to enhance the reliability and safety of the network.

By collecting and analyzing performance indicators, the CPI provides a comprehensive, early evaluation of potential contingency situations the network may face. When arranging the index outcomes in descending order (from top to bottom), contingency situations can be classified by their risk and impact on the system's stability and safety.

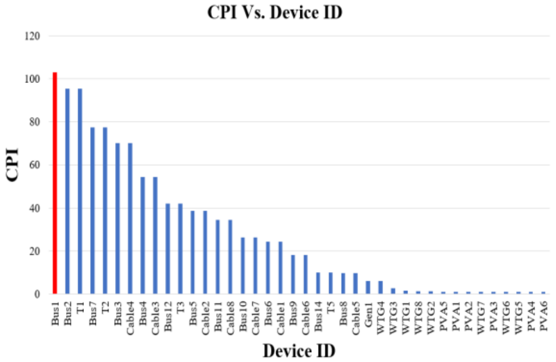
From collecting compound performance indicator data (CPI) as shown in Fig. 10 and Table 11 for all studied Scenarios and comparing them, it can be noted that this indicator provides an accurate proactive vision of the contingency situations that the system may face, in addition to assessing the severity of each case on the stability of the system.

Table 11 compound performance indicator data (CPI)

Outage Device ID	COMPINED (CPI)
Bus1	103.0654
Bus2	95.37309
T1	95.37309
Bus7	77.510843
T2	77.510843
Bus3	70.0287114
Cable4	70.0287114
Bus4	54.3347353
Cable3	54.3347353
Bus12	42.0994192
T3	42.0994192
Bus5	38.7216213
Cable2	38.7216213
Bus11	34.3571615
Cable8	34.3571615
Bus10	26.3383443
Cable7	26.3383443
Bus6	24.2392975
Cable1	24.2392975
Bus9	18.123341
Cable6	18.123341
Bus14	9.963836
T5	9.963836
Bus8	9.536664
Cable5	9.536664
Gen1	6.083831169
WTG4	6.083810971
WTG3	2.558165522
WTG1	1.419228608
WTG8	1.282626248
WTG2	1.2090846
PVA5	0.99273664
PVA1	0.989249656
PVA2	0.989249656
WTG7	0.966346472
PVA3	0.928415763
WTG6	0.907813551
WTG5	0.870937954
PVA4	0.833716515
PVA6	0.833716515

In response to the data extracted from the analysis of contingency situations, Table 9 shows that the first bus separation is the most dangerous contingency scenario. This is attributed to the connection of this bus to the system's main grid, which means that its loss results in a significant reduction in the network's power.

In contrast, the results show that the least effective cases are the PVA 6 outage. This is because most of the power from the PV is relatively small, and most of the network power is directed to the first bus and the close load connected to it through buses, which reduces the effect of PV loss on system stability.



Fig, 10 CPI with Device ID

The comparison between the results of separate performance indicators (such as voltage, real power, reactive power, and excessive loading) and the results of compound indicators (CPI) shows a strong convergence between the two cases. This indicates that the use of the complex indicator is an effective and reliable way to assess critical cases, as it combines the various effects into a single numerical value that facilitates decision-making.

8. CONCLUSION

Based on load flow analysis and a study of the potential contingencies in the proposed system, a set of conclusions were reached.

The Composite Performance Index (CPI) effectively ranks contingencies according to their severity and provides information about the importance of each component in the electrical grid, especially when considering the presence of sustainable power plants. This index combines voltage stability (V/Vsp), real/reactive power flow variations (ΔP/ΔQ), and branch overload (S/Ssp).

This contingency analysis delivers a powerful and practical message: preventing blackouts requires a comprehensive understanding of your grid's vulnerabilities. By subjecting a hybrid power system to a rigorous stress test, the study moves from theoretical principles to real-world numbers, clearly identifying the most significant failures and what we can do about them.

The results provide a very clear picture of the risks. A power outage on Bus 1, a vital link to the main grid, emerged as the most serious threat, with a Composite Performance Index (CPI) of 103.065. This wasn't just a minor glitch; it caused significant voltage drops and widespread outages. Similarly, the T1 outage proved to be a significant risk, resulting in a complete system shutdown and a Composite Performance Index (CPI) of 95.37309. Cable 4 also proved destabilizing, with a Composite Performance Index (CPI) of 70.0287, confirming that some infrastructure lines are true arteries for power flow. In contrast, the outage of a photovoltaic array such as PVA5 had a minimal impact, with a Composite Performance Index (CPI) of 0.99274. The wind turbine outage, like WTG4, also had a small effect, with a Composite Performance Index (CPI) of just 6.0838109707. But its impact was greater than the PV outage. This is not to insult renewables. Rather, it is evidence that their distributed nature can be a strength, making them low-risk assets that enhance resilience without creating critical vulnerabilities. Renewables, such as solar PV, have improved the overall system's resilience. Still, their low contribution to the total power supply means they cannot fully compensate for the loss of essential conventional generators. This highlights the need for a balanced energy mix and smarter grid designs that leverage the strengths of both traditional and renewable sources.

These numbers transform the Energy Performance Index from an academic metric into a key diagnostic tool. A score above 100 indicates a crisis, 70 requires immediate attention, and a score close to 1 is considered a low priority. This allows grid operators to make data-driven decisions and focus their limited efforts and budgets on specific components such as Bus 1 and Cable 4, which we now know are the weakest points in the system. Ultimately, the path to a more resilient grid is not a mystery. This includes strengthening critical vulnerabilities identified by high CPI scores (for example, adding redundancy to Bus 1 or Cable 4); strategically integrating more renewable energy sources, whose low CPI impact demonstrates their potential to diversify our energy mix without introducing significant new risks; and shifting from a reactive "wait and see" approach to a proactive one, using tools such as ETAP and Power Performance Index (CPI) simulation to anticipate problems and activate automated responses such as rolling blackouts or generator rescheduling before one outage becomes a chain. Contingency analysis also helps monitor voltage dips or spikes in public transformers, enabling future response by developing appropriate improvement plans before they occur, ensuring system stability and continued energy supply to consumers.

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