Load Flow and N−1 Contingency Analysis of a 33 kV Industrial Ring Main Distribution Network Using ETAP: A Comprehensive Review

Dr. Nahid khan[1], Pranay Kuthe[2]
[1] *Professor, Department of Electrical Engineering, Tulshiram Gaikwad Patil College of Engineering, Nagpur, Maharashtra, India*
[2] *Research Scholar, Department of Electrical Engineering, Tulshiram Gaikwad Patil College of Engineering, Nagpur, Maharashtra, India*

***Abstract*—Industrial distribution networks necessitate ongoing evaluation of their operating conditions and resilience against equipment failures. A 33 kV ring-main configuration is highlighted as offering enhanced flexibility compared to standard radial feeders, as it allows for continued supply through alternative routes after a failure. The effectiveness of this system is influenced by factors such as bus voltages, feeder loads, transformer usage, power losses, and the existence of alternative power-flow paths. This paper reviews load-flow and N−1 contingency-analysis techniques relevant to 33 kV industrial ring-main networks utilizing ETAP software. It surveys existing scholarship on 33 kV systems, ETAP-based distribution studies, IEEE 33-bus load-flow analyses, voltage performance of feeders, and contingency analysis methods. The focus is on detecting voltage violations, overloaded sections, transformer loads, and key network elements affected by outages. Findings suggest that load flow is essential for establishing base-case conditions for contingency assessment, while N−1 analysis is crucial for evaluating system performance after outages. A significant literature gap is noted, as few accessible studies simultaneously investigate the 33 kV ring-main structure, ETAP load flow, and systematic N−1 contingency assessment, prompting the authors to propose a structured methodology for developing and accessing such models without predetermined numerical values for specific networks.**

***Index Terms*—33 kV distribution network, ETAP, industrial power system, load flow analysis, ring-main network, N−1 contingency, voltage profile, transformer loading.**

I. INTRODUCTION

Reliable electrical power supply is essential for industrial facilities because interruptions can affect production, process equipment, safety systems, and auxiliary services. Industrial distribution systems are therefore designed not only to supply the required electrical load but also to maintain acceptable operating conditions under variations in demand and credible equipment outages. Load-flow analysis is one of the principal steady-state tools used to evaluate these conditions. It provides bus-voltage magnitudes and angles, active and reactive power flows, equipment loading, and system losses.

The importance of load-flow studies is particularly significant in medium-voltage industrial distribution systems. A representative ETAP study demonstrates how transformer loading, increased demand, bus voltage, line loading, and system losses can be evaluated under different operating conditions [1]. Similarly, an industrial power-plant study using ETAP modelled a 220/33 kV supply arrangement and used load-flow results to assess the voltage profile before conducting subsequent fault studies [2].

For a 33 kV industrial distribution system, the network topology has a direct influence on reliability and post-contingency power-flow paths. A radial network normally has a single supply path to downstream loads, whereas a ring-main arrangement can provide an alternative path when switching facilities and equipment ratings permit. Consequently, the normal operating condition alone is insufficient to establish whether a ring-main network provides adequate

operational security. The system should also be examined following credible single-element outages.
This requirement leads to the concept of N−1 contingency analysis, in which one network element is assumed unavailable while the remaining system is evaluated. The objective is to determine whether the post-contingency network continues to satisfy defined operating criteria. Research on an actual 33 kV grid has demonstrated the use of load flow and contingency analysis to identify affected transformers, distribution branches, and weak buses under outage conditions [3]. Although that study used PSS/E rather than ETAP, its 33 kV contingency-analysis framework is directly relevant to the assessment of medium-voltage networks.

ETAP provides an integrated environment for modelling buses, transformers, cables, transmission and distribution branches, loads, generators, and switching devices. Its application to distribution systems has been reported for 33 kV feeders [4], 33/11 kV substations [5], 66 kV substations [6], and industrial networks [1], [2]. These studies demonstrate the usefulness of software-based load-flow modelling for identifying voltage and loading problems before changes are implemented in a physical system.
The purpose of this paper is therefore to review and organize existing research relevant to load flow and N−1 contingency analysis of a 33 kV industrial ring-main distribution network using ETAP. The paper does not claim original simulation results for a particular industrial plant. Instead, it synthesizes published methodologies and findings and identifies a structured approach for future ETAP-based assessment.

The main objectives are:

1. To review load-flow analysis techniques applicable to medium-voltage industrial distribution networks.
2. To examine published ETAP-based studies involving 33 kV and related distribution systems.
3. To review the application of N−1 contingency analysis to 33 kV networks.
4. To identify the operating parameters that should be monitored during normal and contingency conditions.
5. To identify research gaps concerning the combined assessment of 33 kV industrial ring-main networks using ETAP.

FUNDAMENTALS OF LOAD FLOW ANALYSIS

Load-flow analysis evaluates the steady-state electrical condition of power systems based on generation, load, and network parameters. Key outputs include bus-voltage magnitude, voltage phase angle, active and reactive power flow, branch currents, equipment loading, and system losses. The relationship between bus voltages and currents is represented as $[I]=[Y][V]$, with bus-admittance matrix $[Y]$ and bus voltage vector $[V]$. Complex power injected at bus i is given by $S_i=P_i+jQ_i=V_i I_i^*$. Numerical methods like Gauss–Seidel and Newton–Raphson are used for solving nonlinear load-flow equations, with the latter favored for its rapid convergence. The IEEE 33-bus study exemplifies voltage-profile importance, revealing voltage reductions influenced by feeder impedance and load distribution. For industrial networks, crucial results include voltage limits, transformer and loader performance, power flows, power factor, and potential operating violations, forming a basis for contingency studies.

33 kV INDUSTRIAL RING-MAIN DISTRIBUTION NETWORKS

A 33 kV distribution system serves as an intermediary voltage level between high-voltage substations and industrial utility loads. The network's performance is influenced by factors such as feeder length, conductor impedance, transformer capacity, and load distribution. A ring-main configuration allows loads to be supplied from multiple directions, enhancing operational flexibility but not guaranteeing uninterrupted supply. After outages, switching can adjust the network layout, though issues like feeder overload and inadequate voltage may still occur. Studies using ETAP on 33 kV and 66 kV systems highlight the importance of detailed network modeling for assessing voltage profiles and losses, thus emphasizing that real-world network characteristics must inform evaluations over simplified models.

N−1 CONTINGENCY ANALYSIS

N−1 contingency analysis assesses the impact of losing a single network eleent while keeping all other equipment operational. The procedure involves:
(1) solving the base-case load flow;
(2) selecting a network element to disable;
(3) recalculating load flow;

(4) comparing results with operational criteria; (5) restoring the element; and
(6) repeating for other potential outages.

Results can be compiled into a contingency table highlighting outages, minimum bus voltage, maximum branch and transformer loadings, along with violations. Research, including investigations on a 33 kV grid by Teck and Barsoum, showed the method's effectiveness in identifying transformer and distribution issues under single-element outages, while also acknowledging the limitations of N−1−1 scenarios. More recent studies by Rahaman et al. used ETAP-based methods to analyze both N−1 and N−2 conditions, focusing on voltage and reactive-power variables. Credible N−1 cases for industrial systems may include outages of feeder sections, incoming feeders, transformers, generators, and bus sections, with specific contingencies based on the single-line diagram and operational philosophy. It's crucial to ensure that, beyond continuity, the post-contingency conditions for voltage, current, loading, and power flow are acceptable.

ETAP-BASED ANALYSIS METHODOLOGY

ETAP-based assessment involves creating a digital model of an electrical network, specifically for load-flow analysis in a 33 kV industrial ring-main system. The model comprises key components such as utility sources, feeders, buses, and transformers. Initial steps include verifying input data against documentation, followed by a base-case load flow analysis to determine normal operational conditions and identify potential overloads and voltage violations. Contingencies are analyzed by simulating outages, impacting power transfer paths, with results indicated by metrics such as minimum bus voltage and maximum loading. Multiple contingency classes are defined: Case A (no violations), Case B (voltage violation), Case C (thermal overload), Case D (both), and Case E (loss of supply). The effectiveness of ETAP in assessing transformer overloads and voltage violations is supported by literature, confirming its suitability for evaluating the relationship between normal load flow and contingency results in electrical systems.

II. LITERATURE REVIEW

The literature reviewed in this paper can be grouped into four major categories: general ETAP load-flow studies, 33 kV distribution studies, industrial-network studies, and explicit contingency-analysis studies.

A. ETAP-Based Load-Flow Studies

Mehtre and Katakwar presented a practical ETAP load-flow study of a representative distribution system [1]. Their analysis considered different operating conditions, including transformer loading and increased demand. The reported results demonstrate that changes in loading can produce observable effects on bus voltages, line loading, and overall network performance. The study also identifies load flow as a foundation for further contingency and stability investigations.

Mehtre and Chaurasia investigated a 66 kV substation using ETAP and actual substation data [6]. Their work focused on load flow and under-voltage conditions and illustrates how an ETAP model can be developed from practical equipment information rather than a purely theoretical test system.

The 33/11 kV substation study by Rajput, Patil, and Mehtre provides a more voltage-relevant example for medium-voltage distribution systems [5]. The model includes the grid, transformer, cable, circuit breaker, busbar, and load elements. Newton–Raphson load flow was used to evaluate power flow, losses, and voltage behaviour.

These studies support the use of ETAP as a practical modelling environment, but they do not individually provide a complete treatment of an industrial 33 kV ring-main system under systematic N−1 conditions.

B. 33 kV Distribution Studies

The study by Alameen et al. is particularly relevant because it considers an actual 33 kV feeder and models an 18-bus system using ETAP [4]. The authors investigate technical losses and voltage profile and consider additional feeder construction and shunt compensation as improvement measures.

The study is important to the present review because it connects three aspects of distribution-system assessment: network loading, voltage performance, and reinforcement for improved reliability. However, the investigated network is a rural feeder rather than an industrial ring-main system. Consequently, its results should be used as methodological evidence rather than as direct evidence of industrial ring-main behaviour.

The IEEE 33-bus study by Ukut, Okpura, and Tim provides a complementary benchmark perspective [7]. The authors implement Newton–Raphson load flow on the IEEE 33-bus system and obtain bus-voltage and phase-angle results. Although the study is not an industrial ETAP study, the standard test network provides a useful basis for understanding how feeder impedance and load distribution influence voltage performance.

C. Industrial Distribution Studies

The industrial study by Patel, Patel, and Matiyeda combines load flow, short-circuit analysis, and protection-coordination analysis in an industrial distribution network [9]. The work demonstrates the importance of assessing equipment loading and voltage performance under different operating scenarios. It also shows how the same network model can support multiple types of electrical studies.

An industrial power-plant study by Ananya and Mercy used ETAP to model a 220/33 kV supply arrangement and evaluate load flow and fault conditions [10]. The authors reported that the modelled bus voltages remained within the stated permissible range under the investigated load-flow condition. Fault studies were subsequently performed using the system information obtained from the load-flow model.

These studies are directly relevant to the industrial context of the present paper. However, neither represents the complete combination of an industrial 33 kV ring-main topology and systematic N−1 contingency analysis. This distinction is important because normal load flow and industrial fault analysis do not by themselves establish whether an alternative ring path can support the system following a feeder outage.

D. Explicit Contingency Studies

Teck and Barsoum investigate a 33 kV power grid through load flow, contingency analysis, and voltage-stability assessment, highlighting affected transformers and weak buses post-outages. While valuable for contingency analysis, their use of PSS/E does not establish an ETAP-specific workflow. Rahaman et al. expand on this by evaluating a medium-voltage network under N−1 and N−2 outages, combining contingency analysis with performance indices, indicating that simple overload counting may overlook key vulnerabilities. Overall, these studies demonstrate that contingency analysis can reveal critical components that appear non-problematic during normal operations, especially in ring-main networks where outages can significantly shift demand.

E. Comparative Assessment

Table I summarizes the principal characteristics of the reviewed studies.

TABLE I COMPARISON OF RELEVANT RESEARCH STUDIES

Author	Year	Ref	Brief of review	Key findings
V. V. Mehtre and I. Katakwar	2024	[1]	Reviewed load-flow analysis of a distribution power system using ETAP under normal, transformer-overload, and increased-load conditions.	Load flow identifies bus-voltage variations, transformer loading, line loading, and losses; increased loading can produce operating violations.
A. C. and E. L. Mercy	2026	[2]	Reviewed load-flow and fault studies of an industrial power plant modeled in ETAP, including the 220/33 kV supply arrangement and industrial generation/load components.	ETAP provides a practical platform for evaluating industrial-system load flow and fault conditions; voltage profiles were assessed against acceptable limits.

K. H. Teck and N. Barsoum	2018	[3]	Investigated steady-state operation and contingency conditions of a 33 kV power grid, including network equipment outages.	N−1 contingencies can produce branch/transformer loading and voltage violations that are not apparent under normal operation.
A. S. E. Alameen et al.	2021	[4]	Studied a 33 kV distribution feeder using ETAP, with emphasis on voltage profile and technical losses.	ETAP-based analysis can identify voltage-drop and loss problems and evaluate measures for improving feeder performance.
V. Mehtre, A. S. Rajput, and K. Patil	2026	[5]	Presented a case study of a 33/11 kV substation using ETAP, including grid, transformer, cable, breaker, bus, and load models.	Load-flow and short-circuit analysis can be applied to assess medium-voltage substation operating conditions and equipment stresses.
U. I. Ukut, N. Okpura, and P. O. Tim	2023	[6]	Analyzed the IEEE 33-bus distribution system using the Newton–Raphson load-flow method.	The study demonstrates distribution-system voltage and power-flow analysis and provides a benchmark for evaluating load-flow techniques.
H. R. Patel, A. M. Patel, and R. Y. Matiyeda	2026	[7]	Reviewed an industrial distribution network using ETAP for load flow, short circuit, and protective-device coordination studies.	A detailed ETAP model can support multiple industrial power-system studies and identify operating and protection-related issues.
D. A. Rahaman et al.	2026	[8]	Investigated reliability of a 33 kV medium-voltage network using ETAP and evaluated N−1 and N−2 contingencies with voltage and reactive-power performance indices.	Contingency assessment benefits from considering voltage and reactive-power performance in addition to simple equipment loading.
M. Bilal, M. N. Arbab, and M. Zubair	2019	[9]	Presented an ETAP load-flow case study of a 132/11 kV substation.	ETAP load-flow analysis can identify voltage and loading conditions in substation networks and support system-performance evaluation.
V. V. Mehtre and U. Chaurasia	2022	[10]	Studied load-flow performance of a 66 kV substation using ETAP software.	The study demonstrates the use of ETAP for evaluating voltage and power-flow conditions in high-voltage distribution/substation systems.

The comparison indicates that the literature provides substantial evidence for the individual components of the proposed study. ETAP is repeatedly used for distribution and industrial load-flow modelling [1], [4]–[6], [9], [10]. Separate studies address 33 kV networks and contingency performance [3], [4], [8]. Benchmark load-flow research provides additional methodological support [7].

Nevertheless, the intersection of these topics is comparatively less developed. In particular, there is a need for studies that combine:

1. an actual industrial 33 kV ring-main topology;
2. ETAP-based base-case load flow;
3. systematic N−1 outage simulation;
4. post-contingency voltage and equipment-loading assessment; and
5. identification of critical feeder or transformer outages.

This combination represents the principal focus of the proposed review framework.

III. RESEARCH GAPS AND FUTURE SCOPE

The literature review reveals several gaps that are relevant to the development of a 33 kV industrial ring-main contingency study.

A. Limited Integration of Ring-Main Topology and N−1 Analysis

Several publications examine 33 kV feeders or medium-voltage networks, while others investigate industrial ETAP models. However, fewer studies explicitly integrate an industrial ring-main topology with a systematic set of N−1 feeder and transformer outages.

A ring-main network has different post-contingency behaviour from a radial feeder because power may be transferred through an alternative path. Therefore, results obtained from radial 33 kV studies cannot automatically be applied to an industrial ring-main system.

B. Future Integration of Distributed Generation

Industrial networks increasingly include captive generation, waste-heat recovery systems, photovoltaic generation, battery energy storage, or other distributed resources. Their operating status can significantly affect contingency performance.

The future study can therefore compare scenarios such as:

- utility supply only;
- utility plus captive generation;
- utility plus renewable generation;
- generator unavailable;
- one transformer unavailable; and
- one ring feeder unavailable.

Such scenario analysis would establish whether local generation improves or worsens post-contingency voltage and loading conditions.

C. Extension From N−1 to N−1−1 and N−2 Studies

The principal requirement of the proposed paper is N−1 analysis. Nevertheless, the reviewed 33 kV research by Teck and Barsoum demonstrates the value of considering a second outage after the initial contingency [3], while Rahaman et al. explicitly investigate N−2 conditions [8].

A future extension could therefore investigate selected N−1−1 or N−2 cases after the critical single contingencies have been identified. Such an extension should not replace the N−1 analysis but should build upon it.

D. Proposed Research Direction

Based on the reviewed literature, a suitable future investigation would develop an ETAP model of the actual 33 kV industrial ring-main network, solve the normal load flow, and then perform a systematic N−1 assessment. The resulting study should report both the base-case and post-contingency operating conditions.

The proposed sequence is:

Network data → ETAP model → Base-case load flow → Validation → N−1 outage cases → Voltage/loading assessment → Critical contingency identification → Mitigation options.

Possible mitigation measures include feeder reinforcement, transformer capacity enhancement, network reconfiguration, capacitor installation, generation dispatch changes, or controlled load shedding. Each mitigation option should be evaluated against the same load-flow and contingency criteria.

IV. CONCLUSION

This review examined the application of load-flow and N−1 contingency analysis to medium-voltage and industrial distribution systems, with particular emphasis on 33 kV networks and ETAP-based modelling. Existing research demonstrates that load-flow analysis is effective for identifying voltage deviations, transformer overloads, feeder loading, and losses under normal and stressed operating conditions. ETAP has been applied to practical distribution feeders, substations, and industrial electrical networks, including systems incorporating 33 kV equipment.

The reviewed literature also demonstrates the importance of contingency analysis. Studies of 33 kV systems have shown that single-element outages can produce branch overloads and voltage violations even when the pre-contingency system is operating acceptably. ETAP-based contingency studies further demonstrate the usefulness of combining voltage and loading indicators when identifying critical network elements.

However, a specific literature gap remains at the intersection of industrial 33 kV ring-main topology, ETAP load-flow modelling, and systematic N−1 contingency assessment. The ring-main configuration requires particular attention because an outage may transfer power to an alternative feeder and create loading or voltage problems that are not visible during normal operation.

Accordingly, a future study should construct a validated ETAP model of the industrial 33 kV ring-main system, perform a base-case load-flow analysis, systematically simulate credible single-element outages, and assess post-contingency voltage, feeder loading, transformer loading, and losses. Such a methodology would provide a structured basis for determining whether the network can maintain acceptable operation following credible equipment outages and for identifying reinforcement or operational measures where violations occur.

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