MOTIVECTION
Journal of Mechanical Electrical and Industrial Engineering

Volume: 8, Number: 2, 2026
ISSN: 2655 – 7215 [printed] ; 2685-2098 [online]
DOI: https://doi.org/10.46574/motivection.v8i2.555

Task-Level Mapping of Electrical and Oil-Handling Risks during Transformer Oil Purification: A Job Safety Analysis at PT PLN Batam

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ABSTRACT

Transformer oil purification combines electrical isolation, auxiliary power, pressurized oil transfer, dielectric testing, and recommissioning, creating interconnected electrical and oil-handling hazards. This study mapped task-level risks and specified stage-specific controls for the purification workflow at PT PLN Batam using Job Safety Analysis. A single-site case study examined ten stages through observation, 30 maintenance interviews, and operational safety-document review. Hazards were classified retrospectively using a 5 × 5 likelihood–severity matrix. Seven stages were rated high risk and three medium risk. Purification-unit connection received the highest score (15) because electrical and oil-transfer interfaces converge at this stage. Proposed controls emphasize verified isolation, lockout/tagout, competent authorization, pressure-rated connections, containment, spill readiness, and independent restoration checks. Under assumed full implementation and verification, the profile is projected to shift to seven medium-risk and three low-risk stages. The study provides a transparent task-level control map while distinguishing projected residual risk from measured outcomes.

Keywords
Electrical maintenance safety; job safety analysis; oil-handling hazards; residual risk; transformer oil purification

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Submitted : May 16, 2026. Accepted : July 15, 2026. Published : July 28, 2026

INTRODUCTION

Reliable substation operation depends substantially on transformer condition because deterioration of this critical asset can disrupt electricity delivery and increase the technical and operational consequences of failure. Within this asset-management context, mineral insulating oil performs two essential functions: providing dielectric insulation and transferring heat away from active transformer components. Moisture, particulate contamination, oxidation products, and service ageing can progressively degrade the electrical and physicochemical properties of the oil. Consequently, oil-condition assessment and maintenance planning should consider both transformer criticality and the consequences of continued operation under deteriorated conditions [1], [2]. Furthermore, transformer oil purification is performed to restore oil serviceability by circulating the insulating liquid through a treatment unit that removes moisture, dissolved gases, and particulate contamination before the transformer is returned to service. Although this process provides an important maintenance benefit, it also creates an interconnected hazard environment. Electrical isolation and restoration, temporary auxiliary-power connections, pressurized oil transfer, hot or leaking oil, and ignition-sensitive conditions may occur within the same maintenance window.

These interfaces can expose personnel and assets to electric shock, arc flash, thermal injury, pressure release, slips, environmental contamination, and spill-fire escalation [3]–[5]. Therefore, purification safety depends not only on controlling individual hazards but also on coordinating electrical and oil-transfer controls throughout the work sequence. Job Safety Analysis (JSA) is appropriate for this operational problem because it decomposes a job into observable stages, identifies the hazards and credible consequences associated with each stage, and links the required controls to the sequence in which the work is performed. Research on complex industrial maintenance indicates that hazard identification becomes more informative when temporal, spatial, and operational relationships between activities are explicitly represented. Such representation helps preserve a traceable relationship among the task, hazard, consequence, and corresponding control, particularly when several systems are handled simultaneously [6].

JSA should nevertheless be distinguished from, while remaining compatible with, broader risk-assessment approaches. JSA is centred on the sequence of a specific job and is therefore suited to point-of-work decisions. In contrast, Hazard Identification, Risk Assessment, and Risk Control (HIRARC) and Hazard Identification, Risk Assessment, and Determining Control (HIRADC) commonly organize heterogeneous hazards across work areas or processes, whereas Fault Tree Analysis examines combinations of events that may lead to a defined undesired outcome. For transformer oil purification, JSA provides the primary analytical structure because the main concern is determining where and when electrical isolation, oil-transfer integrity, containment, and restoration controls must be verified. Regardless of the selected method, semi-quantitative risk assessment requires explicit likelihood and severity definitions, category thresholds, and a clearly stated decision purpose, because ambiguous matrices may produce inconsistent priorities [7], [8].

Recent electrical-safety research further supports a system-level interpretation of task risk. Risk modelling in power-distribution activities, systematic reviews of electrical-worker competence, and analyses of safety-management practices indicate that risk control depends on the interaction of equipment condition, procedures, supervision, authorization, competence, and organizational monitoring [9]–[11]. Training and personal protective equipment remain necessary, but they cannot independently control every interface created by temporary electrical connections, energy isolation, pressurized oil transfer, and recommissioning. From this perspective, transformer oil purification should be treated as a coordinated control system rather than as a collection of unrelated maintenance activities.

Taken together, the literature reveals a specific operational gap. Transformer studies primarily address oil degradation, condition assessment, and maintenance strategy, whereas occupational-risk studies generally examine broader work environments, individual hazard categories, or maintenance activities without following the complete transformer oil-purification cycle. Evidence remains limited on task-level risk mapping that traces the process from isolation and Purification-unit connection through oil extraction, circulation, dielectric testing, disconnection, and re-energization while explicitly presenting the scoring basis, priority controls, and assumptions underlying projected residual risk [1], [2], [6]–[8]. A general hazard inventory is insufficient for this purpose because it does not clearly identify the stages at which electrical and oil-handling controls converge and require coordinated verification.

Accordingly, this study aims to: (1) decompose transformer oil purification at PT PLN Batam into ten sequential and auditable work stages; (2) classify the initial risk of each stage using a defined likelihood–severity matrix; (3) prioritize stage-specific controls according to the hierarchy of controls; and (4) project residual risk without presenting the projection as measured post-intervention performance. The contribution of this study does not lie in proposing a new JSA method. Instead, it provides a context-specific, task-level application that integrates electrical isolation, oil-transfer containment, control-verification points, and transparent residual-risk assumptions within a complete maintenance sequence. This approach is intended to improve the transparency of risk prioritization and the practical application of JSA in electrical-utility maintenance.

METHOD

Research Design, Study Period, and Unit of Analysis

A descriptive single-site case study was conducted to examine the transformer oil-purification workflow at PT PLN Batam. Field data were collected during scheduled maintenance activities on 20–21 March 2026. The unit of analysis was the complete purification workflow, beginning with equipment preparation and transformer isolation and ending with work-area normalization and transformer re-energization. The source documentation divided the workflow into ten sequential work stages. A task-centred design was used because Job Safety Analysis (JSA) is intended to associate hazards, credible consequences, and controls with the sequence in which work is performed rather than assessing risk only at the general facility level [6], [12].

Evidence Sources and Functional Role Coverage

Evidence was obtained from three sources: direct field observation of work activities and operational interfaces; semi-structured interviews with 30 personnel from the substation (Gardu Induk; GI) maintenance team; and review of the applicable standard operating procedures, JSA forms, inspection records, and available incident documentation. The interview evidence was organized according to four functional contributions: maintenance execution, work supervision, Health, Safety, and Environment (HSE) review, and unit authorization. The interviews were used to triangulate task-level hazards and controls and were not intended to support population-level statistical inference.

Evidence Triangulation Procedure

Evidence triangulation was conducted for each of the ten work stages. Field-observation notes collected on 20–21 March 2026 were compared with the interview accounts and applicable documentary requirements. A hazard or existing control was retained in the analytical record when it was either directly observed or documented in an operational record and was subsequently clarified by the relevant functional role. Items that could not be corroborated were not converted into claims regarding worker behaviour, procedural violation, or accident causation.

Figure 1 presents the functional contributions and evidence pathways used to construct the triangulated JSA record. The pathway represents task contribution, control verification, and authorization functions and should not be interpreted as the formal organizational structure of PT PLN Batam.

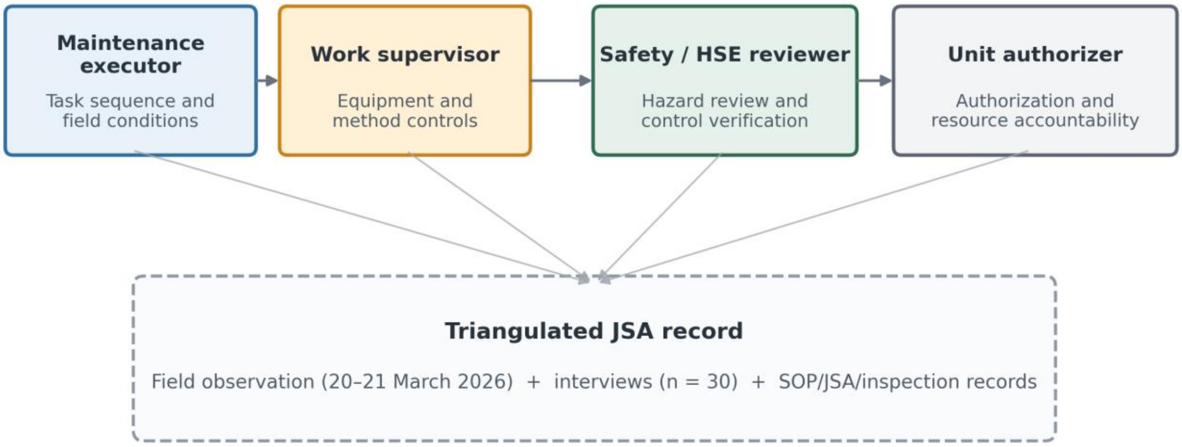

Figure 1. Functional roles and evidence-triangulation pathway used to construct the Job Safety Analysis record.

Job Safety Analysis and Risk-Classification Procedure

The JSA was conducted in five sequential steps: (1) defining the job boundary; (2) dividing the purification workflow into sequential work stages; (3) identifying energy sources, hazardous conditions, and credible consequences at each stage; (4) assigning an initial risk rating; and (5) specifying priority controls and a projected residual-risk rating. This procedure follows the task-sequence logic of JSA and maintains an explicit relationship among work activities, hazards, consequences, controls, and risk priorities [6], [12].

For each work stage, risk was calculated as the product of likelihood and severity:

$$R = L \times S \quad (1)$$

where R is the risk score, L is the likelihood rating, and S is the severity rating. Likelihood and severity were each rated on a five-point scale. Likelihood represented the documented opportunity for exposure during comparable work or within the observed work cycle. Severity represented the credible consequence that could occur if the relevant control failed.

The resulting scores were grouped into four categories: low (1–4), medium (5–9), high (10–16), and extreme (17–25). These categories were used to prioritize control and verification requirements and were not interpreted as statistical estimates of accident probability. Explicit descriptors and category thresholds were retained because risk matrices may produce inconsistent priorities when likelihood, severity, or category boundaries are insufficiently defined [7]. The scoring criteria are presented in Table 1.

Table 1. Criteria for likelihood, severity, and risk-score classification

Likelihood score (L)	Severity score (S)	Risk category (L × S)
1 — Rare: not expected during comparable work	1 — Insignificant: no injury or negligible disruption	Low: 1–4
2 — Unlikely: conceivable but infrequent	2 — Minor: first-aid treatment or short disruption	Medium: 5–9
3 — Possible: could occur during the work cycle	3 — Moderate: medical treatment, contained spill, or repair	High: 10–16

4 — Likely: expected under recurring exposure	4 — Major: serious injury, significant spill or fire, or outage	Extreme: 17–25
5 — Almost certain: repeated or sustained exposure	5 — Catastrophic: fatality, major fire, or system-wide loss	—

Note: The risk scores are analytical classifications derived from documented opportunities for exposure and credible consequences. They are not statistical accident probabilities. The residual scores reported in Table 2 are projected ratings based on assumed full implementation and verification of the specified control package; they are not post-intervention measurements.

Control Selection

Priority controls were organized according to the hierarchy of controls. The control logic emphasized eliminating or isolating hazardous energy where practicable, applying engineering barriers and physical containment, establishing administrative authorization and verification, and using personal protective equipment as the final protective layer. For electrical work stages, the control package included an approved switching order, a permit-to-work system, lockout/tagout (LOTO), testing for the absence of voltage, grounding where required, authorization by competent personnel, and independent restoration checks.. These controls addressed the potential for incorrect switching, incomplete isolation, back-feed or stored voltage, improper temporary auxiliary-power connections, and premature re-energization [3].

For oil-transfer stages, the control package included pressure-rated connections, hose and valve integrity checks, controlled operating parameters, secondary containment, drain protection, spill-response readiness, ignition-source control, and accountable handling of contaminated materials and waste oil. These controls addressed leakage, pressurized release, hot-oil contact, slip exposure, environmental contamination, and spill-fire escalation [5].

Projected Residual-Risk Interpretation

Residual ratings were assigned only after assuming that the complete control package specified for each stage had been implemented and verified. The ratings therefore represent decision-support projections rather than observed reductions in incident frequency, exposure, or consequence. Where the credible consequence of control failure remained fatal or catastrophic, particularly during electrical isolation, connection, disconnection, and re-energization, the severity rating was retained and the projected risk reduction resulted primarily from a lower likelihood of exposure. Where engineering containment was considered capable of limiting the credible outcome of an oil release, both likelihood and severity could be reassessed. Any such reduction represents an analytical assumption within the projected model and not evidence of measured control effectiveness.

This interpretation preserves the visibility of high-consequence hazards and prevents the residual matrix from implying that a written procedure or the presence of personal protective equipment alone has rendered the activity safe [7].

Fishbone Synthesis Procedure

After completion of the stage-level JSA, plausible contributing conditions associated with the high-priority work stages were organized into six categories: people, equipment, environment, procedure, material, and management. The categories were derived from the triangulated observation, interview, and documentary record and were used as a prospective verification framework rather than as a validated root-cause analysis.

RESULTS AND DISCUSSION

RESULTS

The Job Safety Analysis identified ten sequential work stages containing hazards related to electrical isolation and restoration, transformer-oil transfer and containment, and general work-area or test-equipment conditions. Table 2 presents the principal hazards, credible outcomes, initial risk ratings, priority controls, and projected residual-risk ratings for each stage.

Table 2. Stage-level Job Safety Analysis for transformer oil purification

Work step	Principal hazard	Credible outcome	Initial risk	Priority controls	Residual risk
1. Prepare equipment and establish the work area	Poor tool layout; damaged or missing equipment; trip obstruction	Minor injury, equipment damage, or work delay	3 × 2 = 6 Med	Use a pre-job inventory and inspection checklist; define a barricaded laydown area; route hoses and cables away from access paths; reject damaged tools; assign housekeeping ownership.	2 × 2 = 4 Lo
2. De-energize, isolate, and release the transforme r for work	Incorrect switching; incomplete isolation; induced, stored, or back-feed voltage	Electric shock, arc flash, fatal injury, or system trip	2 × 5 = 10 Hi	Apply a permit-to-work and approved switching order; identify every energy source; lock and tag isolation points; test for absence of voltage with a verified tester; apply grounding where required; record independent verification before work starts.	1 × 5 = 5 Med
3. Connect the purification unit, hoses, and auxiliary supply	Unexpected energization; incorrect auxiliary connection; loose hose or coupling; poor alignment	Electric shock, arc event, oil release, or equipment damage	3 × 5 = 15 Hi	Maintain LOTO; allow only authorized, competent personnel; verify phase/voltage and protective grounding of auxiliary supply; secure and label hoses; inspect seals and couplings; complete a two-person connection check before circulation.	1 × 5 = 5 Med
4. Extract and sample transforme r oil	Hose/valve leakage; pressurized release; hot oil; spill onto walking surface or drain	Slip injury, skin contact, environment al contaminatio n, fire, or oil loss	3 × 4 = 12 Hi	Verify hose pressure rating, valve position, and connection integrity; place drip trays and secondary containment; protect drains; stage a compatible spill kit and extinguisher; use closed, labelled sample containers; specify stop-work thresholds and spill-response roles.	2 × 3 = 6 Med

Work step	Principal hazard	Credible outcome	Initial risk	Priority controls	Residual risk
5. Circulate, purify, and replenish oil	Pressure excursion; purifier malfunction; hose rupture; oil leakage; ignition source	Spray exposure, slip, fire, contamination, or equipment damage	3 × 4 = 12 Hi	Monitor pressure, temperature, flow, and oil level within equipment limits; use guarded, pressure-rated hoses; maintain secondary containment; control ignition sources; stop the pump before adjustment; inspect filters and alarms; keep an operator at the unit during circulation.	2 × 3 = 6 Med
6. Conduct breakdown-voltage (BDV) testing	Faulty or uncalibrated tester; contact with test voltage; contaminated sample	Shock, unreliable result, repeated work, or delayed recommissioning	2 × 4 = 8 Med	Use a calibrated, guarded tester; restrict access during the test; follow the approved sampling and electrode-cleaning method; discharge the test cell before handling; document result acceptance and repeat-test criteria.	1 × 4 = 4 Lo
7. Re-inject oil and restore the specified oil level	Overfill; hose/valve leakage; trapped pressure; air ingress; hot oil contact	Spill, fire, contamination, equipment impairment, or slip injury	3 × 4 = 12 Hi	Verify tank capacity and target level; control fill rate; vent as required by the approved procedure; continuously monitor connections and oil level; retain drip trays and drain protection; collect contaminated absorbents and waste oil in labelled containers for authorized disposal.	2 × 3 = 6 Med
8. Stop the unit and disconnect hoses and auxiliary connections	Residual electrical energy; trapped pressure; oil retained in hoses; incorrect removal sequence	Shock, arc, oil spray/spill, or equipment damage	2 × 5 = 10 Hi	Keep the transformer under LOTO; isolate and verify the auxiliary supply; stop, depressurize, drain, and cap hoses before removal; use drip trays; apply the documented disconnection sequence; complete an independent connection-clearance check.	1 × 5 = 5 Med
9. Account for tools, remove waste, and normalize the work area	Unrecovered tools; oily waste; residual spill; trip obstruction	Minor injury, foreign-object damage, pollution, or delayed energization	3 × 2 = 6 Med	Reconcile the tool and material register; inspect the transformer and surrounding area; segregate, label, and transfer oily waste through the approved waste stream; remove barriers only after supervisor acceptance.	1 × 2 = 2 Lo

Work step	Principal hazard	Credible outcome	Initial risk	Priority controls	Residual risk
10. Release LOTO and re-energize the transformer	Premature energization; personnel or equipment remaining in the zone; incorrect restoration; internal defect	Electric shock, arc flash, fatal injury, fire, trip, or outage	2 × 5 = 10 Hi	Use a signed restoration checklist; verify personnel, tools, grounds, valves, and covers are clear; close the permit; remove LOTO only under the authorized sequence; obtain dispatcher clearance; establish an exclusion zone; energize remotely where practicable and monitor abnormal indications.	1 × 5 = 5 Med

The initial risk scores ranged from 6 to 15. Seven stages were classified as high risk: transformer de-energization and isolation (10), purification-unit connection (15), oil extraction and sampling (12), oil circulation and replenishment (12), oil re-injection (12), unit disconnection (10), and transformer re-energization (10). Purification-unit connection had the highest initial score of 15. Equipment and work-area preparation, breakdown-voltage testing, and housekeeping were classified as medium risk, with scores of 6, 8, and 6, respectively. No stage was classified as low or extreme in the initial profile.

After assuming full implementation and verification of the specified control package, the projected residual-risk scores ranged from 2 to 6. Equipment and work-area preparation, breakdown-voltage testing, and housekeeping were projected to become low risk, with scores of 4, 4, and 2, respectively. The other seven stages were projected to become medium risk, with residual scores ranging from 5 to 6. No stage was projected to remain high risk or enter the extreme-risk category. Table 3 summarizes the initial and projected residual-risk distributions.

Table 3. Summary of initial and projected residual-risk classifications by work stage

Risk state	Distribution by work stage
Initial risk	Seven high-risk stages: 2, 3, 4, 5, 7, 8, and 10; three medium-risk stages: 1, 6, and 9; no low- or extreme-risk stages.
Projected residual risk	Seven medium-risk stages: 2, 3, 4, 5, 7, 8, and 10; three low-risk stages: 1, 6, and 9; no high- or extreme-risk stages.

The projected likelihood rating decreased for all ten stages. Severity remained unchanged for stages 1–3, 6, and 8–10. For the oil-handling stages involving extraction, circulation, and re-injection—stages 4, 5, and 7—the projected severity rating decreased from 4 to 3.

Discussion

As shown in Table 2, the high-risk profile was dominated by stages involving transformer isolation, temporary electrical connections, disconnection, and re-energization. This pattern primarily reflects the severity assigned to credible electrical consequences rather than evidence that electrical incidents occur frequently at the study site. Stages 2, 3, 8, and 10 each retained a severity rating of 5 because incomplete isolation, unexpected energization, residual electrical energy, or an incorrect restoration sequence could result in electric shock, arc flash, fatal injury, or system disruption. This interpretation is consistent with electrical-industry risk models that assign substantial priority to exposure involving energized systems and with safety literature emphasizing de-energization, verified absence of voltage, competent work practices, and system-level control [3], [9], [10]. The present findings operationalize this evidence by locating those requirements within specific stages of a transformer oil-purification workflow.

Purification-unit connection produced the highest initial risk score of 15 because it represents a convergence point between electrical and fluid-system conditions. Before oil circulation begins, the transformer isolation status, temporary auxiliary-power supply, equipment alignment, protective grounding, and integrity of hoses, seals, and couplings must all be confirmed. Research on simultaneous industrial maintenance similarly indicates that hazard assessment becomes less reliable when interactions between tasks or systems are examined separately [6]. In the present case, the stage-level analysis identifies Purification-unit connection as a verification interface rather than merely another installation step. A two-person connection check and explicit authorization before circulation are therefore proposed to coordinate electrical and oil-handling verification. These measures are control recommendations derived from the risk map and were not evaluated as completed interventions.

Oil extraction, circulation, replenishment, and re-injection also remained high-priority activities, with initial scores of 12 for stages 4, 5, and 7. These stages combine pressurized transfer, hose and valve integrity, hot-oil contact, walking-surface contamination, drain exposure, and ignition-sensitive conditions. Oil-spill research frames spill management as a sequence of prevention, detection, containment, and recovery rather than reliance on absorbent materials after release has occurred [5]. Transformer-oil fire research further demonstrates that continuous leakage can sustain burning when oil reaches an ignition source [4], while reviews of waste transformer oil emphasize the environmental and occupational consequences of uncontrolled handling and disposal [13]. Accordingly, the control package in Table 2 emphasizes pressure-rated connections, valve-position checks, secondary containment, drain protection, spill readiness, and accountable waste handling.

The projected ratings for stages 4, 5, and 7 reduced both likelihood and severity, from (3 x 4 = 12) to (2 x 3 = 6). This reduction assumes that engineering containment and controlled transfer can limit both the opportunity for release and the credible scale of its consequences. However, because the study did not conduct a prospective post-control evaluation, this severity reduction should be interpreted as an analytical assumption rather than demonstrated control performance. If site conditions allow a major spill, fire, or equipment outage to remain credible despite the proposed controls, the severity rating should remain at 4 and only likelihood should be reduced. This issue should therefore be reviewed during site implementation and future risk recalibration.

The breakdown-voltage testing stage received an initial score of 8 and was classified as medium risk. Unlike work performed directly on the transformer circuit, the test is conducted on an oil sample using a separate test set. Nevertheless, the equipment generates hazardous test voltage, and contaminated sampling vessels, improper electrode preparation, or an uncalibrated tester may produce an unreliable acceptance result. The required control is therefore dual: the tester must be guarded, isolated, and discharged to protect personnel, while sampling and electrode-cleaning procedures must be controlled to preserve measurement quality. Studies of in-service transformer oil similarly indicate that dielectric properties should be interpreted as part of broader oil-condition assessment rather than as an isolated measurement [2].

Beyond the stage-specific ratings, Figure 2 synthesizes six categories of plausible conditions requiring verification: people, equipment, environment, procedure, material, and management. These pathways do not establish that a particular worker violated a procedure or that any branch caused a recorded incident. Instead, the fishbone diagram serves as a prospective verification framework for examining whether task-specific competence, equipment condition, hose routing, LOTO completeness, material control, permit coordination, and independent verification are adequate before work proceeds. This cautious use is consistent with JSA principles that separate hazard identification from unsupported attribution of worker behaviour or accident causation [12].

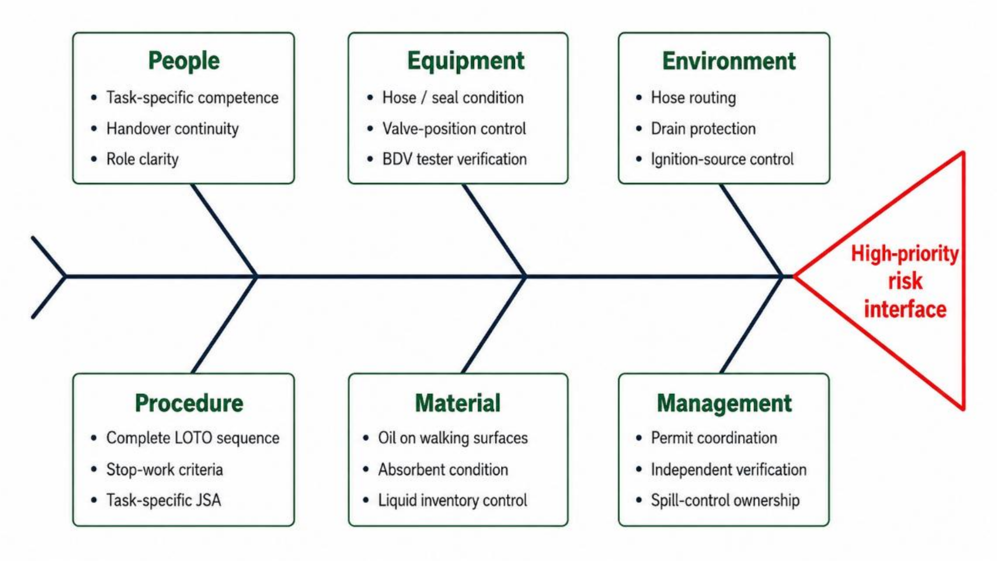

Figure 2. Fishbone synthesis of plausible conditions requiring verification during high-priority electrical and oil-handling stages.

The role pathway in Figure 2 complements the fishbone analysis by showing how evidence and control-verification functions are distributed among maintenance execution, work supervision, HSE review, and unit authorization. Electrical-safety research indicates that competence development is more effective when it is integrated with supervisory, organizational, and system-level controls rather than treated as an isolated training activity [10]. Similarly, studies of electrical-industry safety management associate safety performance with management commitment, communication, worker participation, training, and systematic monitoring [11], [14]. The present role pathway translates these principles into four functional contributions. However, it does not yet assign a named owner or verifier to each control in Table 2; consequently, stage-specific control ownership remains an implementation recommendation rather than an empirically demonstrated study output.

Compared with recent Indonesian occupational-risk applications, the present study retains a familiar semi-quantitative categorization while adapting it to a complete transformer oil-purification sequence. Previous Motivection studies used HIRADC for cleaning-service work, combined HIRA and Fault Tree Analysis for silo operations, assessed mining activities using category-based risk levels, and integrated HIRA with 5S in a workshop environment [15]–[18]. These studies demonstrate the practical value of linking identified hazards to explicit categories and activity-specific controls. However, their work objects and exposure pathways differ from transformer oil purification. The current study extends that applied logic by mapping ten sequential stages in which electrical isolation, temporary auxiliary power, pressurized oil transfer, dielectric testing, and recommissioning occur within the same maintenance window. It also explicitly labels residual ratings as projected, thereby avoiding the implication that control effectiveness has already been measured.

The findings support three implementation priorities. First, Table 2 can be converted into a controlled pre-job checklist containing evidence fields for LOTO, absence-of-voltage testing, auxiliary-supply verification, hose and valve inspection, secondary-containment readiness, and restoration clearance. Second, the seven initially high-risk stages should be assigned named control owners and independent verification points, particularly where responsibility passes between maintenance execution, supervision, HSE review, and unit authorization. Third, future monitoring should record leading indicators such as permit deviations, failed hose inspections, incomplete containment preparation, spill-response readiness, and restoration-check deficiencies. Data-driven electrical-industry research indicates that linking task risk, equipment or worker condition, and rule compliance can strengthen risk monitoring when the underlying data remain traceable and auditable [19]. Such evidence would allow projected residual scores to be recalibrated using observed performance.

Several limitations constrain interpretation of these findings. The study addressed one site and one maintenance process; therefore, transferability depends on transformer design, voltage class, purification-unit configuration, work organization, and local operating procedures. Although 30 maintenance personnel contributed interview evidence, all participants came from the same Gardu Induk maintenance setting, so the findings support qualitative triangulation rather than population-level statistical inference. The likelihood, severity, and residual ratings were retrospective analytical classifications rather than estimated accident probabilities or observed post-intervention outcomes. The scoring procedure did not include a reported measure of assessor agreement, and the fishbone pathways remain hypotheses for verification rather than independently validated root causes.

CONCLUSION

Transformer oil purification at PT PLN Batam was decomposed into ten sequential work stages with distinct electrical, oil-handling, testing, and work-area hazards. The initial assessment classified seven stages as high risk and three as medium risk, with purification-unit connection receiving the highest score of 15 because electrical and oil-system conditions converge at this stage. No stage was classified as extreme. The proposed control strategy prioritizes verified energy isolation, permit-to-work, lockout/tagout, testing for the absence of voltage, competent authorization, connection integrity, pressure control, secondary containment, spill preparedness, waste accountability, and independent recommissioning checks before reliance on personal protective equipment. Under the assumption that the complete control package is implemented and verified, the risk profile is projected to shift to seven medium-risk and three low-risk stages. These projected ratings should be treated as control-verification targets rather than evidence of achieved risk reduction.

The study contributes a transparent, stage-level JSA that links each work stage to its principal hazards, credible consequences, control requirements, and residual-risk assumptions. Its interpretation is limited by the single-site, retrospective design and the absence of prospective control evaluation. Future studies should examine multiple substations, document assessor agreement and exposure frequency, and evaluate control performance using prospective observations and auditable leading indicators.

REFERENCES

[1] H. Guo, Y. Wang, H. Bo, J. Zhang, Y. Yang, and Z. Guo, “Transformer maintenance strategy based on improved risk assessment method considering operation and maintenance costs,” PLOS ONE, vol. 20, no. 12, Art. no. e0338610, Dec. 2025, doi: 10.1371/journal.pone.0338610.

[2] E. Mustafa, B. Ahmad, M. I. Ali, R. S. A. Afia, and R. Ullah, “Degradation assessment of in-service transformer oil based on electrical and chemical properties,” Applied Sciences, vol. 14, no. 24, Art. no. 11767, Dec. 2024, doi: 10.3390/app142411767.

[3] P. Pawenary, H. Purnomo, and W. N. Cahyo, “Safety hazards detections in electrical industry: A systematic literature review,” Engineering Innovations, vol. 17, pp. 49–56, Feb. 2026, doi: 10.4028/p-AqG7RP.

[4] L. Li, P. Chen, R. Sun, X. Zhai, and C. Shi, "The burning characteristics of transformer oil spill fire on horizontal and inclined substrate under continuous leakage condition," Journal of Energy Resources Technology, vol. 145, no. 4, Art. no. 043101, Apr. 2023, doi: 10.1115/1.4056274.
[5] A. C. S. V. de Negreiros, I. D. Lins, C. B. S. Maior, and M. J. das C. Moura, "Oil spills characteristics, detection, and recovery methods: A systematic risk-based view," Journal of Loss Prevention in the Process Industries, vol. 80, Art. no. 104912, Dec. 2022, doi: 10.1016/j.jlp.2022.104912.
[6] S. J. Kwon, S. W. Choi, and E. B. Lee, "Hazard identification and risk assessment during simultaneous operations in industrial plant maintenance based on Job Safety Analysis," Sustainability, vol. 16, no. 21, Art. no. 9277, Oct. 2024, doi: 10.3390/su16219277.
[7] R. C. Jensen, R. L. Bird, and B. W. Nichols, "Risk assessment matrices for workplace hazards: Design for usability," International Journal of Environmental Research and Public Health, vol. 19, no. 5, Art. no. 2763, Mar. 2022, doi: 10.3390/ijerph19052763.
[8] R. Liu, H.-C. Liu, H. Shi, and X. Gu, "Occupational health and safety risk assessment: A systematic literature review of models, methods, and applications," Safety Science, vol. 160, Art. no. 106050, 2023, doi: 10.1016/j.ssci.2022.106050.
[9] M. Sadeghi-Yarandi et al., "Development of a novel Electrical Industry Safety Risk Index (EISRI) in the electricity power distribution industry based on fuzzy analytic hierarchy process," Heliyon, vol. 9, no. 2, Art. no. e13155, Feb. 2023, doi: 10.1016/j.heliyon.2023.e13155.
[10] D. Waugh, S. Newnam, and D. Rodwell, "Systematic review of electrical worker competency interventions: A systems-thinking perspective," Applied Ergonomics, vol. 129, Art. no. 104600, 2025, doi: 10.1016/j.apergo.2025.104600.
[11] O. M. Tawfeeq, S. A. L. Thiruchelvam, and I. Bin Zainal Abidin, "Analyzing safety management practices affecting safety performance in the electrical industry: A systematic review," Engineering, Technology & Applied Science Research, vol. 14, no. 4, pp. 15201–15208, 2024, doi: 10.48084/etasr.7569.
[12] F. Ghasemi, A. Doosti-Irani, and H. Aghaei, "Applications, shortcomings, and new advances of Job Safety Analysis: Findings from a systematic review," Safety and Health at Work, vol. 14, no. 2, pp. 153–162, Jun. 2023, doi: 10.1016/j.shaw.2023.03.006.
[13] R. Tiwari, P. S. Agrawal, P. N. Belkhode, J. V. L. Ruatpuia, and S. L. Rokhum, "Hazardous effects of waste transformer oil and its prevention: A review," Next Sustainability, vol. 3, Art. no. 100026, 2024, doi: 10.1016/j.nxsust.2024.100026.
[14] O. M. Tawfeeq, S. A. L. Thiruchelvam, and I. Bin Zainal Abidin, "Impact of safety management practices on safety performance in workplace environment: A case study in Iraqi electricity production industry," Engineering, Technology & Applied Science Research, vol. 14, no. 2, pp. 13539–13546, 2024, doi: 10.48084/etasr.7006.
[15] S. Damayanti and F. I. Alifin, "Occupational safety and health risk analysis using the HIRADC method on cleaning service workers in the health segment," Motivection: Journal of Mechanical, Electrical and Industrial Engineering, vol. 6, no. 1, pp. 115–124, 2024, doi: 10.46574/motivection.v6i1.306.
[16] M. M. Na'am, D. Andesta, and E. Ismiyah, "Occupational health and safety analysis using HIRA and FTA methods in the silo department of PT. XYZ," Motivection: Journal of Mechanical, Electrical and Industrial Engineering, vol. 5, no. 3, pp. 523–534, 2023, doi: 10.46574/motivection.v5i3.277.
[17] I. Akbar, F. Fadhilah, R. Anarta, and T. G. Saldy, "Analysis of occupational safety risk levels in mining activities at PT Golden Great Borneo, Lahat Regency, South Sumatra Province," Motivection: Journal of Mechanical, Electrical and Industrial Engineering, vol. 6, no. 3, pp. 235–248, 2024, doi: 10.46574/motivection.v6i3.337.
[18] A. Nurissa'adah, E. Ismiyah, and A. W. Rizqi, "Analysis of occupational health and safety in the workshop area using the HIRA and 5S methods at PT. Ravana Jaya," Motivection: Journal of

Mechanical, Electrical and Industrial Engineering, vol. 4, no. 2, pp. 161–174, 2022, doi: 10.46574/motivection.v4i2.122.
[19] D. Lee, D. Lim, and J. Lee, "Safety autonomous platform for data-driven risk management based on an on-site AI engine in the electric power industry," Applied Sciences, vol. 15, no. 2, Art. no. 630, 2025, doi: 10.3390/app15020630.

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