Safety Threshold Framework and Reliability Quantification of Mobile Low-Voltage Loop Closing with Synchronism-Check Supervision

Kien Pham Van*
Faculty of Electrical Engineering
University of Science and Technology - The University of Danang
Da Nang, Vietnam
*pvkien@dut.udn.vn

Thanh Dang Nhat
Faculty of Electrical Engineering
University of Science and Technology - The University of Danang
Da Nang, Vietnam
105210160@sv1.dut.udn.vn

Kiet Mai Van Anh
Faculty of Electrical Engineering
University of Science and Technology - The University of Danang
Da Nang, Vietnam
105210237@sv1.dut.udn.vn

Tri Phan Hien
Da Nang Power Company -
Central Power Corporation
Da Nang, Vietnam
triph@cpc.vn

Viet Ho Quoc
Da Nang Power Company -
Central Power Corporation
Da Nang, Vietnam
hoquocviet2@gmail.com

***Abstract*— Commercial synchronism-check relays are routinely used for generator synchronization and medium-voltage paralleling, but they are not specifically intended for low-voltage transformer loop-closing, where loop impedances are typically as low as 50–150 mΩ. This paper presents a safety and reliability assessment of a mobile low-voltage load-transfer device applied to the Cam Le distribution network of Da Nang Power Company. A phasor-domain analytical model shows that the minimum 6° relay setting can produce circulating currents of 311–414 A for typical 250–400 kVA transformer pairs, equivalent to as much as 2.76 times the 150 A thermal limit of the prototype transfer chain. Consequently, safe short-distance operation must be characterized by a coupled ΔV–$\Delta\varphi$–Z_{loop}–I_{max} constraint envelope with post-close current interlocking, rather than by phase-angle permissive alone. The analysis further shows that increasing cable cross-section may reduce loop impedance and increase loop-closing current, although it improves voltage drop during load transfer. For reliability quantification, 19 actual outage events from the Cam Le network are evaluated using Monte Carlo simulation and deterministic sensitivity analysis. For one device, the estimated benefit is ΔSAIDI=0.054 min/customer/year and ΔENS=996 kWh/year, with a P5–P95 interval of 0.027–0.096. Because the assumed deployment time is approximately 20 min, the device primarily reduces interruption duration and energy not supplied, rather than directly reducing IEEE SAIFI or MAIFI. Extended-distance cases for L=450–500 m reveal a transition from circulating-current constraints to voltage-drop constraints.**

Keyword — low voltage, synchronism check relay, circulating current, distribution reliability, SAIDI, SAIFI, switching device, loop impedance

I. INTRODUCTION

Rapid supply restoration after distribution outages is a central service-quality objective. SAIDI is used by Vietnamese distribution utilities and is consistent with IEEE Std 1366 reliability-index practice [8], [14]. In the Cam Le network, 19 MV unplanned outages from February 2025 to March 2026 caused 170.2 MWh of energy not supplied (ENS) in a study area with N_T = 55,000 customers [2]. Existing service-restoration literature emphasizes feeder-level FLISR, automated reclosers, remote-controlled switches, microgrids and DMS/SCADA [4]-[6], [15]-[17]. These approaches are highly effective but require fixed MV infrastructure and capital investment that may not be immediately available on all feeders.

A practical transitional measure is temporary LV transfer between adjacent 22/0.4 kV distribution transformers [3]. PC Da Nang has practical experience with this operation, but the traditional procedure suffers from three deficiencies: no automatic synchronism supervision, no pair-specific current limit and limited range of field deployment [1]. Without quantitative safety screening, a hard close may generate excessive circulating current; without a deployable switching method, long-duration outages continue until MV repair is completed.

The main literature gap is the absence of a documented framework for mobile LV transformer loop-closing [7], [19]. Commercial Device 25 relays and DER synchronization standards were developed for generator, DER or MV/HV applications [10], [11], not for passive LV transformer paralleling where the impedance regime is two orders of magnitude lower. This paper therefore combines phasor algebra, MCCB/cable constraints and actual CMIS outage replay. The revision further distinguishes the generalizable safety equations from the site-specific Cam Le reliability result, adds a cost-benefit formulation and clarifies operating practices such as deployment time and transformer tap adjustment.

The contributions are: (i) derivation of an LV-specific safe region in the ΔV–Δφ–Zloop space; (ii) proof that phase-angle-only relay settings are structurally insufficient for short LV loops; (iii) an analytical deployment-screening table linking transformer rating, ΔV_{set} and current interlock; and (iv) a bounded reliability estimate using real outage records and uncertainty analysis.

The novelty is deliberately operational rather than algorithmic. Unlike feeder-level restoration optimization, the problem here is whether two already energized LV busbars may be closed through a temporary connector without producing unacceptable circulating current. This requires combining transformer short-circuit impedance [9], temporary-cable resistance, relay setting granularity, MCCB thermal limits, and utility dispatch practice in one reproducible workflow. Therefore, this paper does not present the device as a system-wide automation solution, but rather defines its safe operating envelope for targeted on-site service restoration.

II. PHASOR MODEL AND SAFETY THRESHOLD

A. Definitions and circulating-current model

Let two energized LV busbars B1 and B2 be connected through a temporary cable and MCCB. The immediately established circulating current is

$$I_c = \frac{|V_1 - V_2|}{Z_{\text{loop}}} \tag{1}$$

Define $V_1 = (1 + \varepsilon)V_{ph}\angle 0$ and $V_2 = V_{ph}\angle(-\Delta\varphi)$. Here V_{ph} is the nominal phase voltage; $\varepsilon = (|V_1|-|V_2|)/V_{ph}$ is the relative voltage-magnitude mismatch; $\Delta V = |V_1|-|V_2|$ is expressed in V; $\Delta\varphi$ is expressed in degrees; Z_{loop} is in Ω or mΩ; and I_c is in A. For $|\varepsilon| < 0.10$ and $\Delta\varphi < 10°$, phasor algebra gives

$$|V_1 - V_2| \approx \sqrt{\left(2V_{ph}\sin\frac{\Delta\varphi}{2}\right)^2 + \Delta V^2} \tag{2}$$

The transformer impedance referred to the LV side and the temporary-cable impedance are

$$Z_T = \frac{u_k \cdot V_n^2}{S_{\text{rated}}} \quad ; \quad Z_c \approx r_\sigma \cdot \frac{L}{1000}$$

$$Z_{\text{loop}} = Z_{T1} + Z_{T2} + Z_c \tag{3}$$

For example, a 250+250 kVA pair with uk = 4% has 25.6 mΩ per transformer. With 35 mm² copper cable at L = 50 m, Zc ≈ 26.5 mΩ and Z_{loop} ≈ 77.7 mΩ. Transformer and cable impedances are thus of comparable magnitude, unlike MV/HV applications where source and line impedances are usually much larger.

The fundamental safe-closing condition is

$$\sqrt{\left(2V_{ph}\sin\frac{\Delta\varphi}{2}\right)^2 + \Delta V^2} \le I_{max}Z_{loop} \tag{4}$$

For a selected relay phase-angle setting, a co-optimized voltage threshold is obtained from

$$\Delta V_{set} \le \sqrt{(I_{max}Z_{loop})^2 - \left[2V_{ph}\sin\left(\frac{\Delta\varphi_{set}}{2}\right)\right]^2} \tag{5}$$

Equation (5) shows that fixed ΔV and Δφ thresholds are conservative rectangular approximations of the true safe region. Because the tested relay cannot be set below 6°, ΔV supervision and current interlocking are mandatory for high-rating short-distance pairs.

B. Model assumptions and validity bounds

The model assumes a fundamental-frequency pre-closing assessment. Cable capacitance is negligible for 50-500 m LV cables. The LV loop L/R time constant is typically below one cycle, so the steady-state current gives a useful pre-closure screening metric. Harmonic distortion, severe voltage unbalance, transformer saturation, contact bounce, motor backfeed, inverter-dominated sources and oscillographic transient validation are outside the present model. Thus the equations are transferable only when Z_{loop}, I_{max} and voltage measurements are known and the network remains within normal LV power-quality limits.

For practical replication, the minimum data set is: transformer ratings and uk, actual or assumed tap positions, conductor material and length, measured phase-to-neutral voltages on both sides, MCCB/cable continuous current limit, intended transfer duration, and the affected-load estimate used to compute fi. If any of these inputs are unavailable, the operation should be classified conservatively or blocked until direct field measurement is possible.

III. HARDWARE AND OPERATING WORKFLOW

The prototype includes dual-side voltage measurement, a 70SCRD/70SCRL synchronism-check relay, a motorized NM8N-250C MCCB, auxiliary contacts and pilot interlocks [12], [13]. The close command is permitted only if the synchronism-check contact is healthy, the MCCB open-state contact is confirmed and no trip/interlock flag is present. The device therefore implements a hardware interlock rather than relying on operator observation alone [20].

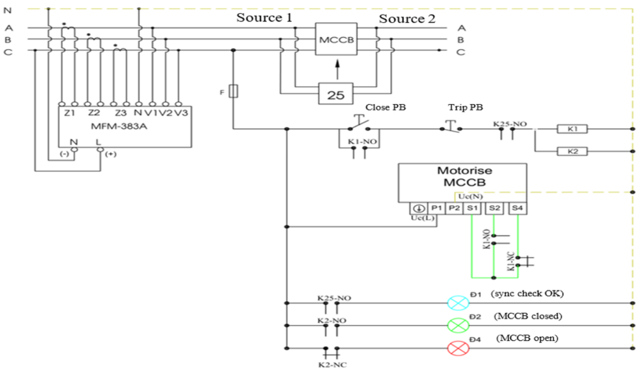

Fig. 1. Control and interlock schematic of the synchronism-check connector using MFM-383A multifunction meter

The close logic can be written compactly as $C_{close} = K_{25} \wedge K_{open} \wedge F_{OK}$, where K_{25} is the synchronism-check permission, K_{open} confirms that the MCCB is still open, and F_{OK} indicates absence of overcurrent or interlock faults. Trip logic is prioritized over close logic. This logic prevents repeated close attempts and ensures that manual intervention does not bypass the calculated safety envelope.

A. Why a 250 A MCCB was selected

The 250 A MCCB was selected as a mobile low-cost prototype standard for partial load transfer, not for full transformer paralleling. The transfer chain is limited by the weakest element: MCCB thermal setting, temporary-cable ampacity and connection hardware. With I_{max} = 150 A and power factor about 0.9,

$$P_{\text{device}} \approx \sqrt{3} \cdot 0.4 \cdot 150 \cdot 0.9 = 93.5 \text{ kW} \tag{6}$$

Consequently, the 150 A continuous prototype rating gives P_{device} = 93.5 kW and is used as a conservative hardware-rating sensitivity. To keep the Cam Le outage replay consistent with the original operational planning assumption, the nominal reliability calculation uses P_{eff} = 125 kW as an effective restored-load block. This P_{eff} value represents the load block that can be restored after practical LV sectionalization and/or an upgraded transfer chain; it should not be interpreted as the continuous current rating of the 150

A prototype. The 630 kVA cases are included as stress tests; frequent operation with 630 kVA transformer pairs would require a larger MCCB frame, higher-ampacity temporary cable, strict ΔV control and mandatory current interlock.

$$\Delta U \approx \sqrt{3} \cdot I \cdot r_\sigma \cdot L$$

Temporary-cable selection must also satisfy voltage drop during load transfer [18]. For a short resistive LV cable, $\Delta U\% \approx (100 \cdot \sqrt{3} \cdot I \cdot r_\sigma \cdot L)/(1000 \cdot V_{LL})$. At I = 150 A and L = 50 m, 35 mm^2 copper gives about 1.70% voltage drop, whereas 50 mm^2 gives about 1.26%. Thus the same design variable has opposite effects: larger conductors improve service voltage after transfer but reduce current-limiting impedance during closure.

B. Deployment time and tap adjustment

The deployment time T_d = 20 min is treated as the effective field time from crew arrival or device availability to successful restoration, including cable placement, voltage verification, synchronism-check confirmation and closing. Long-distance crew travel is not explicitly included; it is represented by the ±50% logistics uncertainty in the Monte Carlo analysis. For system-wide deployment, $T_d^* = T_{travel} + T_{setup} + T_{verification} + T_{closing}$ should be estimated from dispatch data.

In the studied PC Da Nang workflow, tap adjustment is not routinely used as a real-time action solely to satisfy the LV loop-closing ΔV green zone. The 22 kV feeders are often operated at a relatively high feeder-head voltage, approximately 23-24 kV, to reduce MV feeder current and I^2R losses and to improve the remote-end voltage profile. By contrast, 22/0.4 kV transformer tap positions are normally managed as fixed seasonal or planned-operation settings. Therefore, if measured ΔV exceeds ΔV_{set}, closure is blocked and the operator must perform planned tap balancing, choose another transformer pair, reduce transfer load or cancel the operation. The reliability calculation does not assume successful tap adjustment for all candidate events.

IV. SAFETY RESULTS AND DECISION FRAMEWORK

A. Short-distance safety screening

At L = 50 m and 35 mm^2 cable, the 70SCRD minimum phase-angle setting of 6° produces $|V_1 - V_2| = 2V_{ph} \sin(3°) \approx 24.1$V. For a 400+400 kVA pair, Z_{loop} = 58.5 mΩ and $I_c \approx 414$ A. Relative to the 150 A prototype limit,

$$r = \frac{I_c}{I_{\max}} = \frac{414}{150} = 2.76; => k_{I^2} = r^2 \approx 7.62 \quad (7)$$

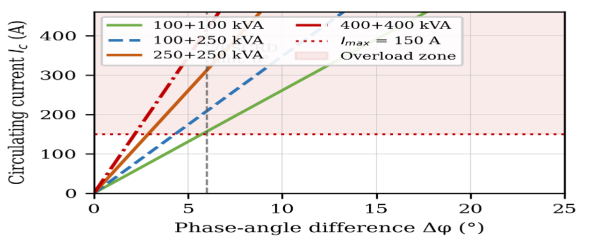

Fig. 2. Circulating current versus phase-angle mismatch at L = 50 m, 35 mm^2 cable.

The factor r is an overcurrent ratio. The squared factor k_{I^2} is only an engineering I^2t stress index for equal exposure time; it is not a replacement for the manufacturer time-current curve. The classification below is therefore a study-specific operating screen, not a universal regulatory threshold.

TABLE I. SAFETY SCREENING COMMON TRANSFORMER PAIRS (35 mm², L = 50 m)

Pair	Z_{loop} (mΩ)	ΔV_{max} (%)	I_c (6°) (A)	Class
100+100	154.5	10.03	157	Marginal
100+250	116.1	7.54	208	Elevated
160+250	92.1	5.98	263	Not OK
250+250	77.7	5.04	311	Not OK
250+400	68.1	4.42	355	Not OK
400+400	58.5	3.80	414	Not OK

Table I shows that phase-angle supervision alone is insufficient for all pairs above 100+250 kVA. The practical remedy is not merely to "adjust the relay," but to replace the MV-oriented phase-angle criterion with a physics-informed ΔV-Δφ-Z_{loop} safety envelope. For a 250+250 kVA pair, ΔV_{max} = 5.04%; the default 10% voltage window would permit hazardous current.

The classification is based on $r = I_c/I_{max}$ and practical operation time. r ≤ 1 is acceptable; 1 < r ≤ 1.2 is marginal because the thermal curve may still allow operation but leaves little allowance for measurement error or ambient temperature; 1.2 < r ≤ 1.5 is elevated risk; and r > 1.5 is treated as not acceptable for this prototype. These categories are used only as an engineering screen for the NM8N-250C transfer chain and must be recalculated for another MCCB, cable or ambient condition.

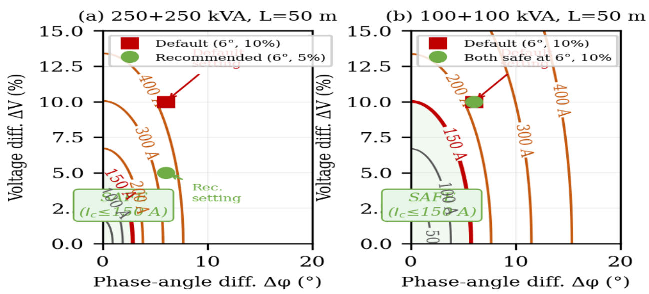

Fig. 3. Safe operating zones for 250+250 kVA and 100+100 kVA transformer pairs.

B. Cable cross-section and distance crossover

In radial design, larger cables are usually preferred. In loop-closing, however, the cable also acts as a current-limiting element. Increasing the cross-section from 35 mm^2 to 50 mm^2 reduces Z_c and therefore increases Ic. For a 400+400 kVA pair at 6°, I_c rises from 414 A to 468 A. For 630+630 kVA, I_c can exceed 500 A, confirming that the 250 A prototype is not appropriate for unrestricted high-rating transformer paralleling.

TABLE II. LARGE-TRANSFORMER COMPARISON AT L = 50 M

Pair	I_{c35} (A)	I_{c50} (A)	$\Delta V_{max35/50}$
250+250	311	341	5.04/4.60%
400+400	414	468	3.80/3.36%
250+630	389	436	4.04/3.60%
400+630	460	528	3.42/2.98%
630+630	517	605	3.04/2.60%

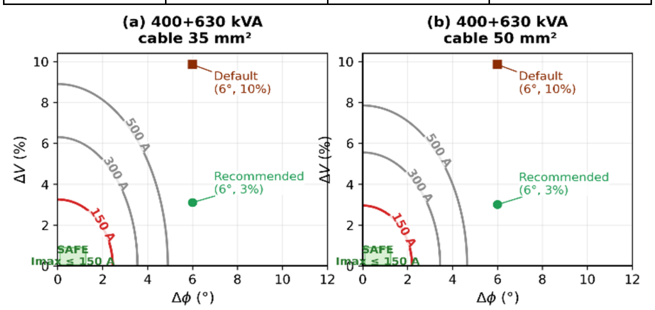

Fig. 4. Safe operating zones for a 400+630 kVA pair with 35 mm^2 and 50 mm^2 cables.

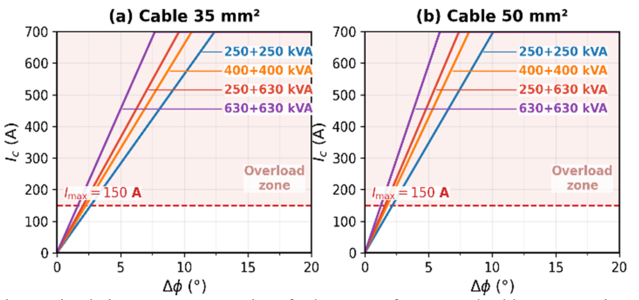

Fig. 5. Circulating-current comparison for large transformers and cable cross-sections.

At long inter-substation distances the binding constraint reverses. Cable impedance becomes large enough to limit Ic, but voltage drop becomes excessive. For 250+250 kVA with 35 mm^2 cable, I_c falls from 311 A at 50 m to about 84 A at 450 m; however ΔU increases from 1.70% to 15.33%. The design problem therefore changes from a synchronization-safety problem at short L to a voltage-quality problem at long L.

TABLE III. DUAL CONSTRAINT FOR 250+250 KVA, 35 MM^2 CABLE

L(m)	Ic (A)	ΔU (%)	Constraint
50	311	1.70	Current
100	233	3.40	Current
210	150	7.14	Crossover
300	113	10.21	Voltage drop
450	84	15.33	Voltage drop

TABLE IV. SAFETY SCREENING AT L = 450 M, 35 MM^2 CABLE

Pair	Z_{loop} (mΩ)	Ic (A)	r	ΔV_{max}
100+100	363.8	66	0.44	23.63%
250+250	287.0	84	0.56	18.64%
400+400	267.8	90	0.60	17.40%
630+630	256.1	94	0.63	16.64%

C. Decision framework

The field workflow is: (1) input transformer ratings, uk, cable size and length; (2) compute Z_{loop}; (3) measure both busbar voltages and compute ΔV and Δφ; (4) calculate ΔV_{set} from (5); (5) verify voltage drop and Pdevice; (6) classify the operation; and (7) apply corrective action if needed. The close command is blocked whenever any safety or transfer-capacity constraint is violated.

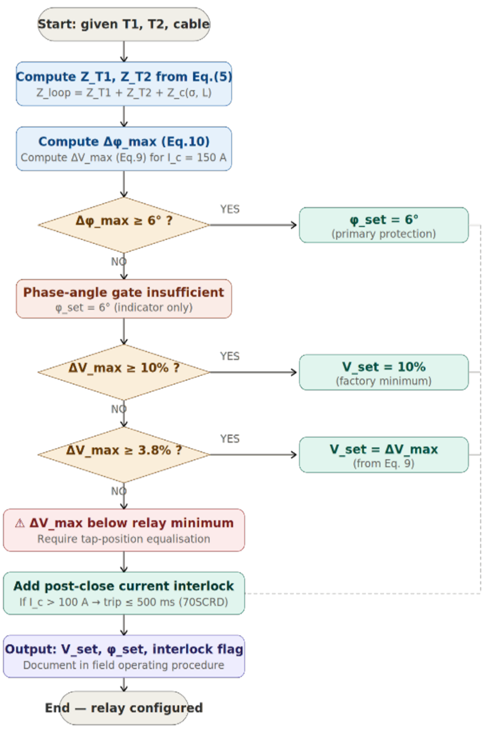

Fig. 6. Four-step relay-setting and closure-screening algorithm.

TABLE V. ANALYTICAL DEPLOYMENT SCREENING SETTINGS FOR SHORT-DISTANCE TRANSFER

Pair	ΔVset	Interlock	Action
100+100	10%	Recommended	Verify phase and current
100+250	7%	Mandatory	Pre-close Δφ check
160+250	6%	Mandatory	ΔV–Δφ–I screen
250+250	5%	Mandatory	ΔV=5%, Δφ check
250+400	4%	Mandatory	Tap balance or alt. pair
400+400	4%	Mandatory	Alt. pair/upgraded chain

The 6° value is the minimum available relay phase-angle setting, not the analytical safe phase-angle limit for all transformer pairs. Corrective actions are ordered as follows: verify the measured voltage values; attempt planned tap balancing if operationally allowed; select an alternative transformer pair with higher Z_{loop} or smaller ΔV; reduce intended transfer current; use a longer or higher-impedance temporary link only if voltage drop remains acceptable; or cancel the operation. This sequence prevents the reliability calculation from implicitly assuming that every candidate outage is closable.

V. RELIABILITY QUANTIFICATION

A. Dataset and per-outage calculation

The reliability assessment uses 19 CMIS outage records from the Cam Le network. Only seven events are eligible for LV transfer; weather/lightning events were excluded because they generally involve broader feeder or source conditions that a local LV transfer device cannot address. This screening makes the reported benefit conservative and bounded by outage type.

TABLE VI. CLASSIFICATION OF 19 OUTAGES BY INTERVENTION ELIGIBILITY

Cause	n	ENS (MWh)	Eligible
Weather/lightning	12	153.2	No
Equipment failure	5	12.2	Yes
Construction	1	1.7	Yes
Other/fire	1	3.1	Yes
Total	19	170.2	7 events

For eligible event i, the restored fraction is computed from the explicitly declared planning-equivalent restored power, $f_i = \min(1, P_{eff}/P_{affected,i})$, with P_{eff} = 125 kW in the nominal replay. The conservative 150 A prototype sensitivity uses P_{device} = 93.5 kW.

$$f_i = min\left\{\frac{P_{device}}{P_{affected,i}}, 1\right\} \quad (8)$$

The annualized reliability contribution is $\Delta SAIDI_i = N_i f_i (t_i - T_d)/N_T$ and $\Delta ENS_i = P_{eff}(t_i - T_d)/60$, where T_d = 20 min and N_T = 55,000 customers.

TABLE VII. PER-OUTAGE RELIABILITY CONTRIBUTION

ID	t	f_i	ΔSAIDI	ΔENS
479/CDO	72	0.0625	0.0059	108
471/CDO	61	0.0417	0.0047	85
474/CDO	39	0.0625	0.0022	40
473/CDO	189	0.0833	0.0192	352
477/CDO	77	0.0833	0.0065	119
476/CDO	129	0.0250	0.0124	227
472/LTR	51	0.0625	0.0035	65
Total	-	-	0.054	996

The result is modest at system level but practically meaningful for targeted long interruptions. The three longest eligible events account for approximately 76% of the benefit. The device therefore has maximum value as an emergency restoration tool for extended outages, not as a substitute for automatic fault isolation.

The small numerical value of ΔSAIDI should be interpreted against the scale of the intervention. One mobile LV unit restores only a bounded fraction of load, typically fi < 0.10 in the recorded events. A reduction of 0.054 min/customer/year corresponds to about 3,000 avoided customer-minutes for N_T = 55,000 customers, achieved without installing fixed MV switching equipment. This is a targeted operational benefit, not a system-wide automation claim. Because customer-level load mapping is unavailable, the calculation assumes proportionality between restored kW and restored customer-minutes.

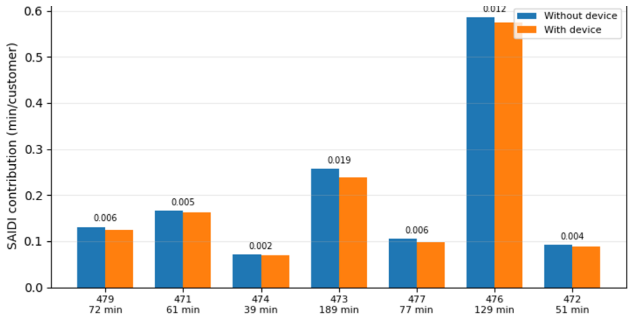

Fig. 7. Per-outage SAIDI comparison before and after mobile LV transfer.

B. Index interpretation and uncertainty

The device reduces interruption duration and ENS. It does not directly reduce IEEE SAIFI or MAIFI under the present $T_d \approx$ 20 min workflow because the affected customers still experience a sustained interruption exceeding the 5 min momentary-interruption threshold. A "restored-customer equivalent" may be reported for operational planning, but it should not be labelled as standard SAIFI unless restoration is completed before the sustained-interruption threshold or is performed preventively.

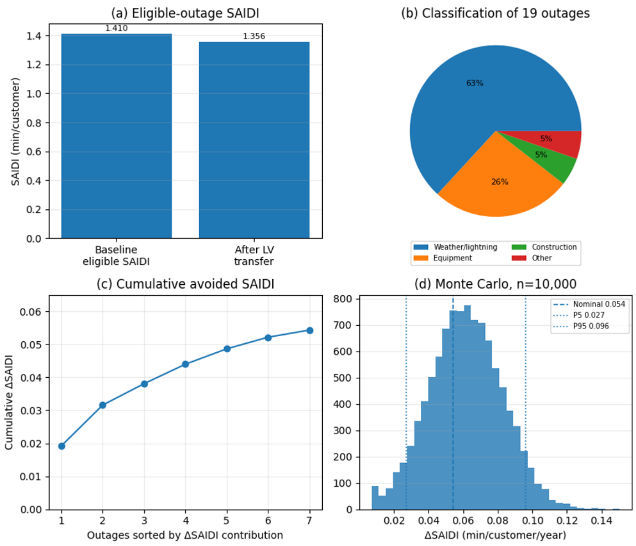

Fig. 8. Reliability summary: before/after SAIDI, outage classification, cumulative contribution and Monte Carlo histogram.

For the same reason, CAIDI should be interpreted carefully. If the outage event is still registered as sustained for the affected customers, the device reduces severity for a restored fraction but does not necessarily improve the frequency denominator. Therefore, this paper reports ΔSAIDI and ΔENS as the primary performance metrics, and treats the discussion of SAIFI/MAIFI/CAIDI as an index-interpretation note.

The Monte Carlo analysis uses 10,000 samples with N_T varied ±27%, customer/load estimation ±40%, T_d ±50% and load factor β ±40%. For the P_{eff} = 125 kW nominal replay, the resulting ΔSAIDI distribution has a nominal value of 0.054 min/customer/year with P5–P95 = 0.027–0.096. A deterministic sensitivity check gives 0.047, 0.054 and 0.063 min/customer/year for conservative, nominal and optimistic cases, respectively. Using the continuous 150 A prototype value P_{device} = 93.5 kW instead of P_{eff} gives a conservative lower-bound estimate of ΔSAIDI = 0.041 min/customer/year and ΔENS = 745 kWh/year. T_d is the most actionable parameter: reducing T_d from 20 to 16 min increases the recoverable portion of long eligible outages, supporting pre-positioning near high-risk areas.

VI. ECONOMICS, GENERALIZATION AND LIMITATIONS [21]

The mobile device does not compete with FLISR or MV reclosers by absolute SAIDI magnitude. It is a low-capital complementary solution for feeders where comprehensive automation has not yet been installed. A concise annualized assessment can be written as

$$\begin{cases} B = VOLL \cdot \Delta ENS + B_{reliability} + B_{operational} \\ C_a = CRF(i,n) \cdot C_{cap} + C_{O\&M} \end{cases} \quad (9)$$

If only avoided energy sales are considered, the economic case remains weak because ΔENS is still modest at 996 kWh/year for one device in this dataset. The value proposition is mainly avoided customer-interruption cost, faster emergency restoration, mobility, and delayed or targeted investment before full automation. With a prototype cost of about 50 million VND, the device is most attractive where eligible long-duration outages and nearby LV source pairs are recurrent.

A break-even assessment should therefore use local VOLL or customer damage cost rather than retail energy price alone. The device becomes more attractive when it is pre-positioned in areas with industrial or commercial loads, repeated long-duration faults, limited backfeed paths and available adjacent LV sources. Conversely, it is not economically justified where outages are short, weather-dominated, or where FLISR already restores supply within seconds to minutes.

For positioning, manual LV transfer is cheapest but unsupervised; the proposed device adds synchronization and interlocking at low capital cost; MV reclosers and FLISR deliver much larger SAIDI reduction but require fixed infrastructure, communications and higher investment.

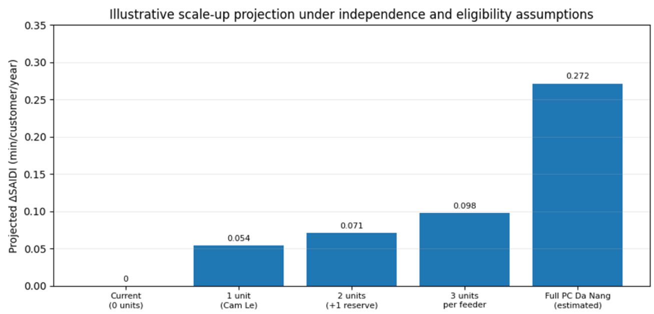

Fig. 9. Scale-up projection of mobile LV transfer units in PC Da Nang context.

The analytical safety framework is transferable to other LV networks if transformer impedance, cable data, voltage measurements and protection limits are available. The numerical ΔSAIDI = 0.054 min/customer/year and ΔENS = 996 kWh/year are site-specific to Cam Le under the declared P_{eff} = 125 kW planning case and must not be generalized directly. The continuous 150 A prototype sensitivity is lower, at ΔSAIDI = 0.041 min/customer/year and ΔENS = 745 kWh/year. Further limitations include the small 19-event dataset, lack of oscillographic field validation, absence of a full crew-travel model, and reliance on manufacturer MCCB data rather than repeated field trip tests.

Threats to validity are grouped into four categories. Measurement threats include CMIS load-estimation error and unrecorded customer-side switching. Model threats include the steady-state approximation and neglect of saturation/contact bounce. External-validity threats include the single-network dataset and the seasonal nature of tap settings. Implementation threats include crew availability, cable handling time, ambient temperature and operator compliance. These threats were made explicit so that future utilities can reproduce or refine the framework using their own data.

VII. CONCLUSION

This paper reformulates mobile LV loop-closing as an impedance-dependent safety problem coupled with a bounded reliability calculation. The minimum 6° synch-check setting is insufficient for common short-distance LV transformer pairs, producing up to 2.76 times the 150 A prototype limit. The main short-distance safety condition is not a single ΔV_{max} threshold, but a combined ΔV–$\Delta\varphi$–Z_{loop} envelope supported by post-close current interlocking. Larger cable cross-section reduces voltage drop but increases closing current, while long cable lengths reverse the constraint from circulating current to voltage drop. For one mobile unit in the Cam Le case, the declared P_{eff} = 125 kW replay gives ΔSAIDI = 0.054 min/customer/year and ΔENS = 996 kWh/year, with uncertainty bounds P5–P95 = 0.027–0.096; the 93.5 kW continuous prototype sensitivity gives 0.041 min/customer/year and 745 kWh/year. The paper deliberately avoids overclaiming SAIFI/MAIFI reduction under a 20 min deployment time and positions the device as a low-cost complement to MV automation. Safe implementation requires pair-specific ΔVset, phase verification, voltage-drop screening, current interlock and field validation before routine deployment.

ACKNOWLEDGMENT, DATA AVAILABILITY, AND AI-USE STATEMENT

The authors acknowledge the research project “Research and Development of a Mobile Switching Device for Low-Voltage Distribution Network Loop Closing” and Da Nang Power Company for operational context and anonymized CMIS outage records used in this study. The CMIS data are internal records and are not publicly released; aggregated values required for reproducibility are reported.

REFERENCES

[1] PC Da Nang, “Research and fabrication of a mobile LV loop-closing switching device,” internal technical proposal, in Vietnamese, used with permission.
[2] Cam Le Power Management Team, “CMIS outage database 02/2025-03/2026,” PC Da Nang, anonymized internal data, used with permission.
[3] M. A. A. Al-Jaafreh and G. Mokryani, “Planning and operation of LV distribution networks: A comprehensive review,” IET Energy Syst. Integr., vol. 1, no. 3, pp. 133-146, 2019.
[4] F. Shen, Q. Wu, and Y. Xue, “Review of service restoration for distribution systems,” J. Mod. Power Syst. Clean Energy, vol. 8, no. 1, pp. 1-14, 2020.
[5] M. Rodríguez-Montañés, J. A. Rosendo-Macías, and A. Gómez-Expósito, “A systematic approach to service restoration in distribution networks,” Electr. Power Syst. Res., vol. 189, Art. no. 106539, 2020.
[6] Y. Xu, C.-C. Liu, K. P. Schneider, and D. T. Ton, “Placement of remote-controlled switches to enhance distribution system restoration capability,” IEEE Trans. Power Syst., vol. 31, no. 2, pp. 1139-1150, 2016.
[7] Y.-L. Ke, “The design criteria and operational constraints for parallel operation of transformers,” IEE Proc.-Gener. Transm. Distrib., vol. 150, no. 6, pp. 717-721, 2003.
[8] IEEE Guide for Electric Power Distribution Reliability Indices, IEEE Std 1366-2022, 2022.
[9] Power Transformers - Part 5: Ability to Withstand Short Circuit, IEC 60076-5, 2006.
[10] IEEE Standard for Electrical Power System Device Function Numbers, Acronyms, and Contact Designations, IEEE Std C37.2-2008.
[11] IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces, IEEE Std 1547-2018, 2018.
[12] Chint Electric, “NM8N moulded case circuit breaker,” product catalog, 2021.
[13] Broyce Control, “70SCRD/70SCRL synch-check relay,” datasheet, document 70SCR-C1999-05-06.
[14] Vietnam Ministry of Industry and Trade, “Circular 39/2015/TT-BCT on distribution-system reliability indices,” 2015.
[15] A. Zidan et al., “Fault detection, isolation, and service restoration in distribution systems: State-of-the-art and future trends,” IEEE Trans. Smart Grid, vol. 8, no. 5, pp. 2170-2185, 2017.
[16] E. L. Campoverde et al., “Service restoration in distribution systems considering priority customers and microgrids,” Electr. Power Syst. Res., vol. 237, Art. no. 110988, 2024.
[17] K. Liang, H. Wang, D. Pozo, and V. Terzija, “Power system restoration with large renewable penetration: State-of-the-art and future trends,” Int. J. Electr. Power Energy Syst., vol. 155, Art. no. 109494, 2024.
[18] T. A. Short, Electric Power Distribution Handbook, 2nd ed. Boca Raton, FL: CRC Press, 2014.
[19] Z. Wang et al., “A pre-synchronization strategy for grid-forming loop-closing device in distribution network,” in Proc. IEEE PES General Meeting, 2022, pp. 1-5.
[20] Functional Safety of Electrical/Electronic/Programmable Electronic Safety-Related Systems, IEC 61508, Ed. 2.0, 2010.
[21] U.S. DOE Grid Deployment Office, “Monitoring and control technologies resilience investment guide,” 2024.