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Genetic algorithm optimization of recloser placement for reliability improvement and energy not supplied reduction in a 20 kV radial feeder

Ramdhan Halid Siregar[1,*], Fitria Kamal[2], Mahdi Syukri[3], Syahrizal[4]
[1,2,3,4]Department of Electrical and Computer Engineering, Faculty of Engineering, Universitas Syiah Kuala, Banda Aceh, Indonesia

**Corresponding Author: ramdhan@usk.ac.id*

ABSTRACT

Reliability of medium-voltage radial feeders depends strongly on where protective devices are installed. This study determines the best location for one additional recloser on the 20 kV KT-02 Paya Dapur feeder (35 nodes, 34 segments, 1,980 customers), which already has a recloser at segment Z17. A genetic algorithm (GA) implemented in MATLAB searches 33 candidate segments, and the customers affected by each fault are derived from protection-zone boundaries rather than from topology alone. The objective function combines the normalized system average interruption frequency index (SAIFI), the system average interruption duration index (SAIDI), and energy not supplied (ENS) under three weighting scenarios, while an ETAP load-flow study checks the effect on power losses. The baseline feeder records a SAIFI of 4.6135 interruptions/customer/year, a SAIDI of 13.8405 h/customer/year, and an ENS of 3,942.48 kWh/year. Weighting only SAIFI and SAIDI (50/50), or SAIFI, SAIDI, and ENS at 40/40/20, selects Z24, which cuts SAIFI and SAIDI by 20.07% and ENS by 3.65%. Raising the ENS weight to 50% moves the optimum to Z12, with reductions of 19.48% and 4.75%, which reveals a trade-off between interruption frequency and lost energy. Power losses stay at 7.7979 kW before and after installation. Even with the extra recloser, SAIFI remains above the 3.21 benchmark of SPLN 59:1985, but adding a second recloser at Z12 to the Z24 solution lowers it to 2.79.

Keywords: Recloser placement, Genetic algorithm, Radial distribution system, Reliability indices, Energy not supplied

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1. INTRODUCTION

Reliability of electricity supply is one of the main indicators of distribution service quality. Short circuits, phase-to-phase faults, and ground faults on overhead medium-voltage lines interrupt supply and cause economic and social losses [1], [2]. Many feeders are built in a radial pattern because it is the simplest and cheapest arrangement, but its weakness is that a fault anywhere on the line de-energizes every customer fed through the device that clears it [3]. An automatic circuit recloser addresses this weakness: it opens on fault current and closes again automatically, so a transient fault does not turn into a long outage, while a permanent fault is confined to the zone behind the recloser [4], [5]. Three indices are used here to judge a placement. SAIFI and SAIDI are the standard interruption indices for utility benchmarking, and they describe how often and for how long customers lose supply. ENS is added because it measures how much energy is lost, and so separates placements that interrupt the same number of customers but different amounts of load.

Choosing where to put a recloser is a combinatorial problem. The answer depends on network structure, load level, fault records, and technical and economic limits [6], [7]. A poorly chosen location raises investment cost without a meaningful reliability gain and can complicate protection coordination. Population-based metaheuristics are therefore attractive, and the genetic algorithm (GA) is among the most widely used. It improves a set of candidate solutions generation by generation through selection of fit individuals, recombination, and occasional mutation [8], [9].

Optimal switching-device placement in radial systems was formulated early by Billinton and Jonnavithula [10]. More recent work applies evolutionary search to recloser siting. Alam *et al.* [11] reported that a GA gave the most consistent results among three solvers for a radial feeder, with a standard deviation of 0.09% over 100 runs against 0.17% for differential evolution and 0.14% for mixed-integer nonlinear programming. Ferraz *et al.* [12] used genetic optimization for distributed energy resource allocation together with recloser–fuse coordination, and Srivastava *et al.* [13] and Lyubchenko *et al.* [14] addressed reliability improvement through GA-based and optimal recloser allocation. Safari *et al.* [15] combined recloser and sectionalizer placement with coordination, fault type, and equipment malfunction, Ghosh *et al.* [7] paired value-based auto-recloser placement with network remodelling, and Kahouli *et al.* [16] compared GA and particle swarm optimization for reliability-oriented reconfiguration.

The studies in [11]–[14] establish that evolutionary search can locate reclosers, with objectives centered on reliability improvement [11], [13], [14] or on protection coordination [12]. Two modelling choices deserve more attention. First, counting every downstream customer as affected overlooks that the nearest upstream recloser, not the fault location, sets the boundary of an outage. Second, SAIFI and SAIDI describe how often and how long customers are interrupted but say little about how much load is lost, which is what energy not supplied (ENS) captures. This paper therefore examines explicitly how the choice of weights among these indices moves the optimum. The protection-zone affected-customer matrix proposed here is the main novelty of this study: it ties every candidate location to the outage boundary set by the nearest upstream recloser, so that SAIFI, SAIDI, and ENS are all evaluated on the same, protection-consistent basis.

This paper determines the best location for one additional recloser on a real 20 kV feeder of PT PLN (Persero), the KT-02 Paya Dapur feeder served by ULP Kota Fajar, South Aceh, Indonesia. The feeder was selected because its baseline SAIFI of 4.6135 interruptions/customer/year is about 44% above the SPLN 59:1985 benchmark of 3.21 [17], and because it is long (38.89 km) and serves 1,980 customers behind a single recloser, so any fault upstream of Z17 interrupts the whole feeder. The contribution is threefold: (i) an affected-customer matrix built from protection-zone boundaries on real feeder data; (ii) a normalized objective of SAIFI, SAIDI, and ENS that is tested under three weighting scenarios to expose the sensitivity of the optimum; and (iii) a load-flow check in ETAP of the technical effect of the placement. The remainder of the paper describes the method (Section 2), presents and discusses the results (Section 3), and closes with conclusions (Section 4).

2. RESEARCH METHOD

The study is simulation based. The reliability model and the GA were implemented in MATLAB R2023b, and the feeder was modelled in ETAP 19.0 for load-flow analysis. Feeder data and the single-line diagram were provided by ULP Kota Fajar. The overall procedure is shown in Figure 1.

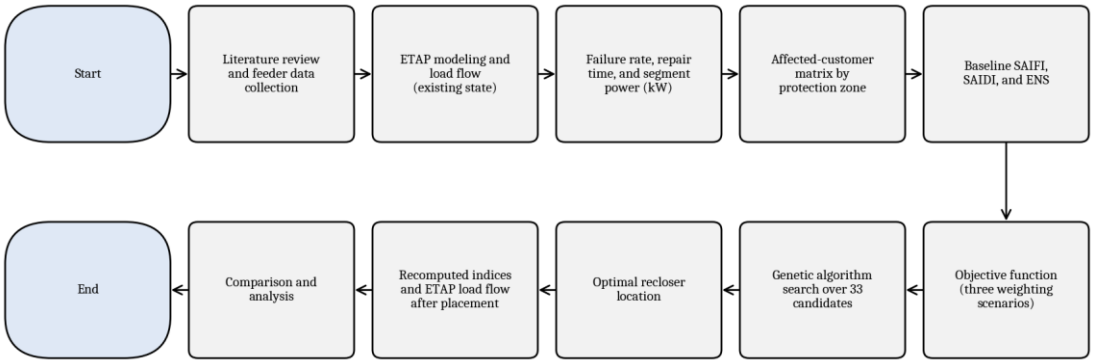


Figure 1. Research procedure.

2.1. Feeder description and data

The KT-02 Paya Dapur feeder is a 20 kV radial feeder with 35 nodes (T1–T35, where T1 is the source node at the switching substation), 34 line segments (Z1–Z34) with a total length of 38.89 km, and 1,980 customers (Figure 2). One recloser is installed on segment Z17, between nodes T17 and T18. It divides the feeder into an upstream part (Z1–Z16), where any fault is cleared by the substation protection and therefore affects all 1,980 customers, and a downstream part (Z17–Z34), where a fault affects the 849 customers behind the recloser. All segments except Z17 are candidate sites for the additional recloser, giving 33 candidates. The segment data used in the computation are listed in Table A1 (Appendix).

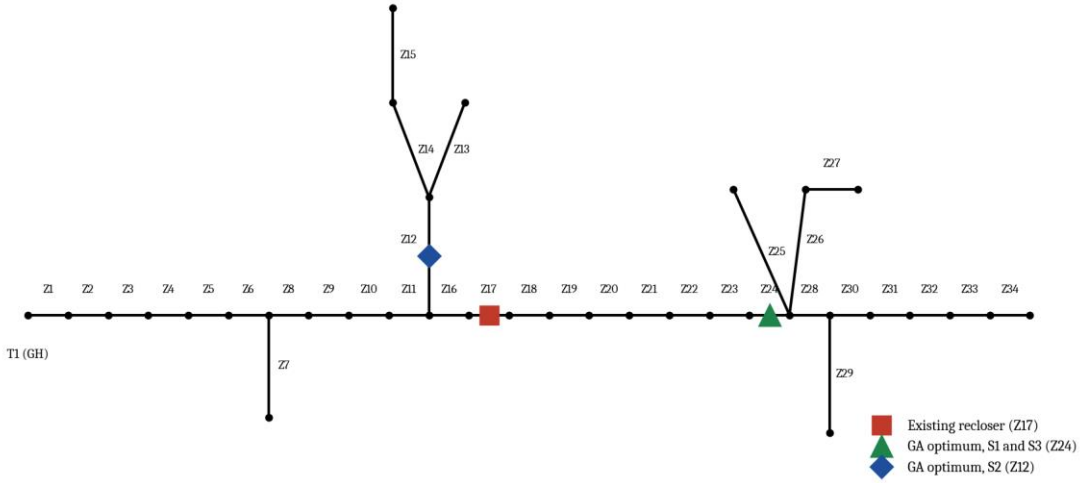


Figure 2. Schematic of the KT-02 Paya Dapur feeder with the existing recloser (Z17) and the optimal locations found by the GA.

Utility records were not sufficient to estimate failure statistics, so the failure rate and repair time were taken from SPLN 59:1985 [17]. Table 1 lists the feeder characteristics and these parameters. The segment failure rate follows from the segment length as in (1), and the annual outage duration of a segment follows from (2).

Table 1. Feeder characteristics and reliability parameters

Parameter	Value	Note
Nominal voltage / topology	20 kV / radial	
Nodes / segments	35 / 34	T1–T35 / Z1–Z34

Total line length	38.89 km	Sum of segments
Total customers (N_T)	1,980	
Existing recloser	Z17	Between T17 and T18
Candidate locations	33	Z1–Z34 except Z17
Failure rate (λ_0)	0.2 faults/km/year	SPLN 59:1985
Repair time (r)	3 h per fault	SPLN 59:1985 (assumed constant; see Section 3.5)
SPLN 59:1985 benchmarks	SAIFI 3.21; SAIDI 21.09	Per customer per year

$$\lambda_i = \lambda_0 L_i \quad (1)$$
$$U_i = \lambda_i r_i \quad (2)$$

2.2. Reliability indices and affected customers

The reliability indices follow the standard definitions [18]. For a feeder with n segments and N_T customers, SAIFI and SAIDI are given by (4) and (5), where A_i is the number of customers interrupted by a permanent fault on segment i.

The number of customers interrupted is determined by protection zones. For a fault on segment i, the interruption is limited by the nearest recloser located at or upstream of that segment, denoted R_i^*, and A_i equals the number of customers downstream of it, as in (3). If no recloser lies upstream, the substation protection clears the fault and $A_i = N_T$. Evaluating (3) for every segment and every candidate location gives an $n \times m$ affected-customer matrix with $n = 34$ segments and $m = 33$ candidates, which is built once and then serves as the search space of the GA. A recloser does not change the failure rate of any segment. It only changes how many customers a fault reaches.

$$A_i = \mathrm{D}(R_i^*) \quad (3)$$
$$\mathrm{SAIFI} = \frac{\sum_{i=1}^{n} \lambda_i A_i}{N_T} \quad (4)$$
$$\mathrm{SAIDI} = \frac{\sum_{i=1}^{n} U_i A_i}{N_T} \quad (5)$$

ENS is estimated from the active power carried by each segment. Let kW_i be the active power flowing through segment i in the ETAP load-flow solution of the existing configuration. The power interrupted by a fault on segment i and the resulting annual ENS are given by (6) and (7).

$$P_{\mathrm{aff,i}} = kW_i \times \frac{A_i}{N_T} \quad (6)$$
$$\mathrm{ENS} = \sum_{i=1}^{n} U_i P_{\mathrm{aff,i}} \quad (7)$$

2.3. Objective function and genetic algorithm

Each index is normalized by its baseline value, computed with the existing recloser at Z17, so that the baseline fitness equals one and smaller values indicate better performance. The objective function is the weighted sum in (8), with $w_1 + w_2 + w_3 = 1$.

$$F = w_1 \frac{\mathrm{SAIFI}}{\mathrm{SAIFI}_0} + w_2 \frac{\mathrm{SAIDI}}{\mathrm{SAIDI}_0} + w_3 \frac{\mathrm{ENS}}{\mathrm{ENS}_0} \quad (8)$$

Three weighting scenarios were tested to examine how priorities shift the optimum: scenario S1 uses SAIFI/SAIDI/ENS weights of 50/50/0, so only reliability drives the choice and ENS is evaluated afterwards; S2 uses 25/25/50, giving ENS the same weight as the two reliability indices together; and S3 uses 40/40/20. Power losses, cost, and protection coordination are not part of the objective.

For reproducibility, the computation was organized as follows. First, the segment data (length, customers per node, and ETAP segment power; Table A1) are read and the radial tree is built from the from–to node pairs. Second, equation (3) is applied to all 34 segments for each of the 33 candidate locations, which gives the 34 × 33 affected-customer matrix once. Third, the baseline SAIFI, SAIDI, and ENS are computed with the recloser at Z17 only, using a failure rate of 0.2 faults/km/year and a repair time of 3 h. Fourth, the GA starts from an initial population of 20 individuals drawn at random from the candidates, and each individual is evaluated by reading its column of the matrix, computing (4)–(7), and combining the results in (8). The same procedure and GA settings are used for S1, S2, and S3, so the three scenarios differ only in their weights.

Each individual carries a single integer gene that encodes one of the 33 candidate segments. The population evolves through tournament selection, crossover, mutation, and elitism, and the individual with the lowest fitness at termination is reported as the optimum [19], [20]. The GA settings are listed in Table 2. These settings were adopted from the ranges commonly used for GA in the literature [19], [20] and were not obtained from a separate tuning study; the exhaustive check in Section 3.2 is used to confirm that they reach the global optimum. The search stops after 100 generations or earlier if the best fitness does not improve for 20 consecutive generations.

Table 2. Genetic algorithm parameters

Parameter	Value
Population size	20
Maximum generations	100
Crossover probability	0.8
Mutation probability	0.1
Elitism	2 individuals
Tournament selection	2 individuals
Early stopping	20 generations without improvement

2.4. Load-flow check

After the optimal locations were found, the indices were recomputed with the added recloser, and the ETAP load flow was repeated to obtain total active power losses before and after installation. Losses are reported only as a technical check. They are not part of the fitness and do not influence the choice of location [21], [22].

3. RESULTS AND DISCUSSION

3.1. Baseline reliability

With the recloser at Z17 only, the feeder has a SAIFI of 4.6135 interruptions/customer/year, a SAIDI of 13.8405 h/customer/year, and an ENS of 3,942.48 kWh/year. These values correspond to $\sum \lambda_i A_i$ = 9,134.70 and $\sum U_i A_i$ = 27,404.10. Against the SPLN 59:1985 limits, SAIFI exceeds the 3.21 interruptions/customer/year benchmark, whereas SAIDI is within the 21.09 h/customer/year benchmark [17]. Because a single repair time of 3 h is applied to every segment, SAIDI is exactly three times SAIFI throughout this study.

3.2. Optimal recloser locations

Table 3 summarizes the outcome of the three scenarios. S1 and S3 both select Z24, which reduces SAIFI to 3.6876 and SAIDI to 11.0627, a reduction of 20.07% for both, and ENS to 3,798.55 kWh/year, a reduction of 3.65%. S2 selects Z12 instead, with SAIFI of 3.7147, SAIDI of 11.1441 (19.48% reduction), and ENS of 3,755.33 kWh/year (4.75% reduction). The fitness of the selected solution is 0.7993 in S1 (20.07% below baseline), 0.8789 in S2 (12.11%), and 0.8321 in S3 (16.79%).

Table 3. Reliability results for the existing configuration and the optimal locations

Parameter	Existing (Z17)	Z24 (S1, S3)	Z12 (S2)
SAIFI (interruptions/customer	4.6135	3.6876 (−20.07%)	3.7147 (−19.48%)

/year)			
SAIDI (h/customer/year)	13.8405	11.0627 (−20.07%)	11.1441 (−19.48%)
ENS (kWh/year)	3,942.48	3,798.55 (−3.65%)	3,755.33 (−4.75%)
Fitness, S1 (50/50/0)	1.0000	0.7993	0.8052
Fitness, S2 (25/25/50)	1.0000	0.8814	0.8789
Fitness, S3 (40/40/20)	1.0000	0.8321	0.8347

The two solutions work in different ways, which explains the change of optimum. A recloser at Z24 splits the downstream zone of Z17 into Z17–Z23, which still affects 849 customers, and Z24–Z34, which affects only 461. That tail contains 11 segments totalling 23.63 km, about 61% of the feeder length, so it carries a large share of the fault exposure. Faults there no longer interrupt the 388 customers in between, and SAIFI falls by 0.926 interruptions/customer/year. A recloser at Z12, in contrast, sits at the head of a lateral of four segments (Z12–Z15, 5.00 km) serving 199 customers. Faults on this lateral currently clear at the substation and interrupt all 1,980 customers. With Z12 they affect only 199, and SAIFI falls by a slightly smaller 0.899. Because ENS weights each segment by its own power flow and by the share of customers interrupted, removing feeder-wide outages from the lateral gives a larger ENS reduction (4.75%) than the Z24 solution (3.65%).

Consistency of the optimization was checked by evaluating all 33 candidates exhaustively for each scenario. Because the search space is this small, the exhaustive ranking gives the exact global optimum, and it coincides with the GA result in S1, S2, and S3 (Table 4 lists the four best candidates).

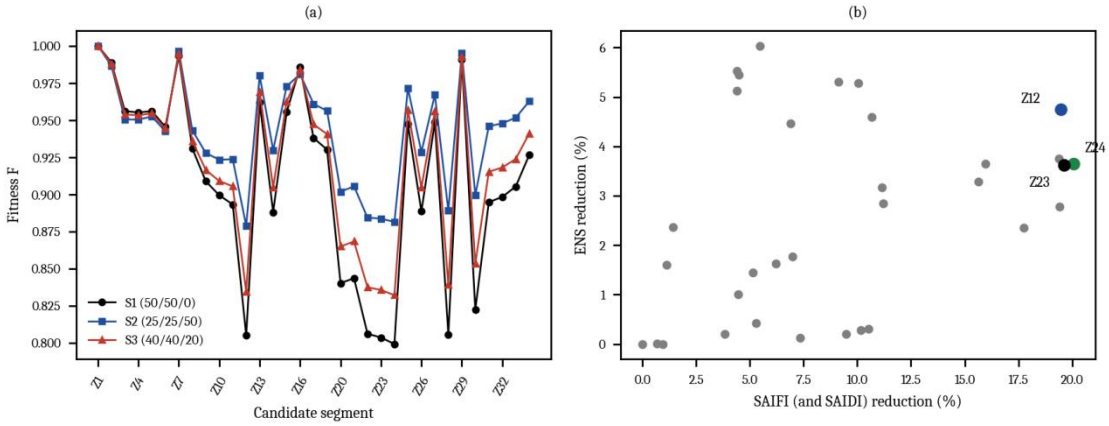


Figure 3. (a) Fitness of all 33 candidate locations in each scenario (S1, S2, S3 weights in parentheses are SAIFI/SAIDI/ENS). (b) SAIFI (and SAIDI) reduction against ENS reduction for each candidate.

3.3. Effect of the weights and robustness of the optimum

Figure 3 and Table 4 show that the choice between Z24 and Z12 is governed by the weight on ENS. At a weight of 20% (S3) the reliability indices still dominate and Z24 remains optimal, and only at 50% (S2) does Z12 take over. The set of near-optimal candidates is small and stable: Z24, Z12, Z23, and Z22 occupy the first four ranks in every scenario except S1, where Z28 replaces Z22. The margins are narrow, however. In S1, Z24 leads Z23 by about 0.5% of fitness, and in S2, Z12 leads Z24 by about 0.3%. A planner should therefore treat these locations as a short list and let field constraints, such as access, communication coverage, and coordination with existing devices, decide among them.

Table 4. Four best candidates in each scenario (fitness values)

Rank	S1 (50/50/0)	S2 (25/25/50)	S3 (40/40/20)
1	Z24 (0.7993)	Z12 (0.8789)	Z24 (0.8321)
2	Z23 (0.8036)	Z24 (0.8814)	Z12 (0.8347)

3	Z12 (0.8052)	Z23 (0.8837)	Z23 (0.8357)
4	Z28 (0.8057)	Z22 (0.8844)	Z22 (0.8375)

Two further observations follow from the data. First, as repair time is constant, SAIFI and SAIDI are proportional, so they reduce by identical percentages and the SAIDI term adds no independent information to the objective. Segment-specific repair times from utility outage records would remove this redundancy. Second, even the best placement leaves SAIFI at 3.69 interruptions/customer/year, about 15% above the SPLN 59:1985 benchmark of 3.21. One additional recloser improves reliability appreciably but does not by itself bring the feeder into compliance.

Practical recommendations for the utility follow from these results. First, the additional recloser should be installed at Z24, or at Z12 if reducing ENS is given priority. Second, because Z24 and Z12 act on different parts of the feeder, the model was also evaluated with both installed: SAIFI falls to 2.7888, SAIDI to 8.3664 h/customer/year, and ENS to 3,611.39 kWh/year, which brings SAIFI below the 3.21 benchmark, so a two-recloser scheme is the more effective way to meet the standard. Third, sectionalizers or additional fuse cutouts on the long laterals beyond Z24 would narrow the zone affected by each fault further and allow the healthy section to be restored before repair; their effect should be quantified by extending the affected-customer matrix to these devices. Fourth, recording outage duration by segment would replace the constant repair time and make later placement studies more accurate. The two-recloser result comes from exhaustive evaluation with the same model and has not yet been checked in ETAP or against a protection-coordination study.

3.4. Power losses

The ETAP load flow gives total active losses of 7.7979 kW for the existing configuration and the same 7.7979 kW after the recloser is placed at Z24, a change of 0.00%. This is expected: a recloser is a normally closed protection device, so in steady state it simply carries the load current like a closed switch and changes neither the path of power flow nor the network configuration. Its internal (contact) impedance is very small compared with the line impedance and is neglected in the ETAP model, so the resistive (I^2R) losses of the feeder are unchanged. The benefit of the placement is therefore confined to reliability, and losses cannot be used to justify or to discriminate between candidate locations.

3.5. Comparison with earlier work and limitations

The finding that a GA locates a recloser position that reduces SAIFI and SAIDI is consistent with earlier GA-based studies [11], [12], [13]. A direct numerical comparison with [11]–[14] is not meaningful, because those studies use different feeders, failure data, and objective definitions. In [11], the GA was judged by its run-to-run dispersion; here the exhaustive check over 33 candidates serves the same purpose by confirming that the GA solution is the global optimum. The present results add that the optimum depends on whether load-weighted ENS is included in the objective, and that SAIFI-oriented and ENS-oriented solutions can lie on different parts of the feeder. Several limitations should be kept in mind. The failure rate and repair time come from a national standard rather than from feeder records. In particular, a constant repair time of 3 h is assumed for every segment, which is why SAIDI and SAIFI change by identical percentages. In practice, repair time depends strongly on how accessible the fault location is, so segment-specific durations could change the ranking of candidates, especially on the long laterals beyond Z24. ENS is estimated from load-flow power and the share of affected customers rather than from metered transformer loads. Only one additional recloser is considered, and cost, protection coordination, and restoration by switching are excluded.

4. CONCLUSION

A GA with a protection-zone-based affected-customer matrix was used to locate one additional recloser on the KT-02 Paya Dapur feeder, and the following conclusions are drawn.

(1) The existing configuration has a SAIFI of 4.6135, a SAIDI of 13.8405, and an ENS of 3,942.48 kWh/year, so SAIFI exceeds the SPLN 59:1985 benchmark. (2) Weighting only reliability (S1) or reliability plus 20% ENS (S3) selects Z24, which lowers SAIFI and SAIDI by 20.07% and ENS by 3.65%. Weighting ENS at 50% (S2) selects Z12, with reductions of 19.48% and 4.75%, so the optimum depends on the priority set in the objective. (3) Power losses are unchanged at 7.7979 kW, so the placement affects reliability only. (4) SAIFI remains above its benchmark after the placement, which indicates that adding a single recloser is not yet adequate to reach the reliability standard. (5) Installing reclosers at both Z24 and Z12 would bring SAIFI to 2.79, below the benchmark, so a two-recloser scheme is the practical next step for the utility.

Future work should use measured failure and repair records, transformer-level load data for ENS, a multi-objective formulation that returns the trade-off set without fixed weights, and the placement of more than one recloser together with other protective devices, including cost and coordination.

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APPENDIX

Table A1. Segment data of the KT-02 Paya Dapur feeder (length, ETAP power flow through the segment, and customers at the receiving node)

Segment	From node	To node	Length (km)	Power flow (kW)	Customers at to-node
Z1	T1	T2	1.5	1005.5	53
Z2	T2	T3	0.726	976.4	171
Z3	T3	T4	0.2	889	10
Z4	T4	T5	0.217	883.8	1
Z5	T5	T6	0.258	883	66
Z6	T6	T7	1.67	849.4	177
Z7	T7	T8	0.158	5.04	10
Z8	T7	T9	0.2	753.2	177
Z9	T9	T10	0.2	663.8	93
Z10	T10	T11	0.33	616.8	93
Z11	T11	T12	0.11	569.7	1
Z12	T12	T13	1.3	100.3	15
Z13	T13	T14	0.896	15.12	30
Z14	T13	T15	1.7	77.6	26
Z15	T15	T16	1.1	64.48	128
Z16	T12	T17	0.625	468.9	80
Z17	T17	T18	1.7	428.4	109
Z18	T18	T19	0.25	373	15
Z19	T19	T20	0.59	365.4	166
Z20	T20	T21	0.612	281.7	1
Z21	T21	T22	0.5	281.1	77
Z22	T22	T23	0.323	242.3	10
Z23	T23	T24	0.1	237.2	10
Z24	T24	T25	0.1	232.2	82
Z25	T25	T26	3	22.66	45
Z26	T25	T27	4	81.09	1
Z27	T27	T28	3.4	80.55	160
Z28	T25	T29	1.2	87.11	33
Z29	T29	T30	0.506	0.499	1
Z30	T29	T31	5.43	69.99	93
Z31	T31	T32	0.213	23.15	1
Z32	T32	T33	0.556	22.65	25
Z33	T33	T34	1.22	10.07	10
Z34	T34	T35	4	5.03	10

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