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Permanent Closed-Loop Operation as a Measure for Improving Power Supply Reliability in a Rural Medium Voltage Distribution Network

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Abstract. Power supply reliability is one of the critical elements of power quality. Its improvement in medium voltage distribution systems in urban areas is typically achieved by cabling. Unfortunately, this approach is often too expensive to be applied in rural areas. One of the possible alternative solutions that can be used in rural medium voltage distribution networks is permanent closed-loop operation. It requires the introduction of additional reclosers with properly parametrized protection relays enabling directional protection. This paper focuses on the case study performed in the 20 kV rural distribution network of Elektro Celje d.d.. Two feeders, where the reliability of the power supply was low, were analyzed. Results of techno-economical evaluation eliminated cabling as a viable solution. The permanent closed-loop operation was selected and implemented after proper placement and parameterization of relays with directional protection functions. The results of two years operation in permanent closed-loop arrangement of feeders show substantial improvement in the reliability of power supply.

Key words. rural medium voltage distribution network, permanent closed-loop operation, power supply reliability.

1. Introduction

Permanent operation with feeders in the closed-loop arrangement is a rarity in medium voltage distribution networks, although the idea is not new [1]. The feasibility study regarding the transition from permanent open-loop to the permanent closed-loop operation of feeders is given in [2]. The reduction in line losses and harmonic distortion that can be achieved in this way is discussed in [3], [4]. The load flow control and voltage profile-related problems are discussed in [5] and [6].
This paper focuses on improving power supply reliability in a rural 20 kV distribution network that supplies a ski resort Slovenia. The power supply reliability was low and must be improved, while cabling of the entire feeder was related to high costs. After performing analysis of the discussed distribution network shown in Fig. 1, where existing switching devices are marked with triangles, a decision was made to replace some of the existing switching devices containing directional protection relay functionalities and introduce some additional switching devices. A schematic presentation of the discussed distribution network with equipped relays (R) is shown in Fig. 2. From this presentation, it is clear that some relays are directional.

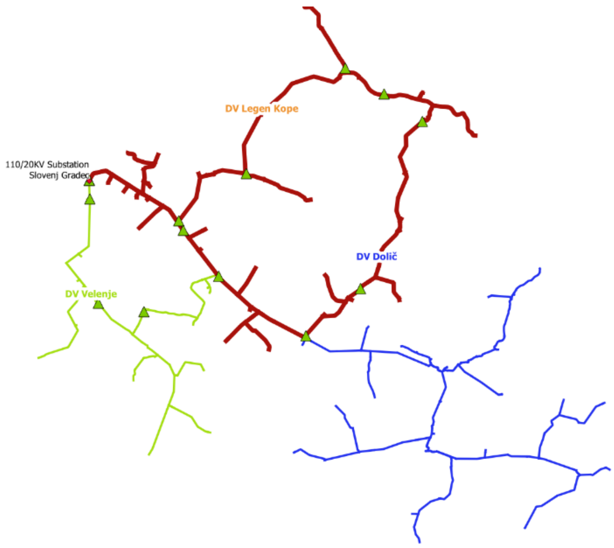

Fig.1. Discussed 20 kV network (tringles mark positions of switching devices)

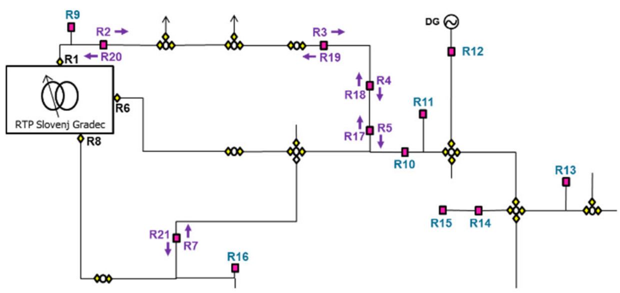

Fig.2. Discussed 20 kV network equipped with switching devices with protection relays (R)

The results of the performed techno-economic analysis focused on the feeders DV Legen Kope (relays R1, R2, R3, R19, and R20) and DV Dolič (Relays R4, R5, R6, R17, and R18) supplying the ski resort Kope, showed, that this solution enables a substantial improvement in the power supply reliability at approximately 20 % of the costs for cabling.

2. Protection system setting

In order to provide proper operation of the protection system suitable for permanent closed-loop operation of the feeders DV Legen Kope and DV Dolič, proper selectivity and sensitivity of all relay pairs was crucial.
The same procedure for optimisation of timing coordination was proposed for the over current (OC) and for the earth fault (EF) protections. Inverse IEC curves were used [7-9], where the operating time t is calculated by:

$$t = TDS\frac{A}{\left(\frac{I}{I_{\mathrm{pu}}}\right)^{B}-1} + T_{\mathrm{add}} \tag{1}$$

where I denotes the rms value of a current measured by a relay. Relay setting are denoted as:

- I_{pu} pick-up current setting,
- TDS time delay setting,
- T_{add} additional time delay,
- A, B constants according to curve type (Table I).

Table I. – Constants for IEC inverse curves

Inverse type	A [s]	B
Extreme	80	2

Selectivity is achieved by timing coordination, where the relay intended to operate (primary relay) operates faster than other relays (back-up relays). Definition of a coordination time interval (*CTI*) is demonstrated in Fig. 3 for a fundamental relay pair consisting of a single primary and back-up relay, where I_{SC} is value of the current corresponding to the fault location at primary relay point. In order to achieve selectivity over an entire range of currents, the following conditions must be fulfilled:

$$t_{\mathrm{b}} - t_{\mathrm{p}} > CTI \quad \text{and} \quad t_{\mathrm{pu,b}} > t_{\mathrm{pu,p}} \tag{2}$$

where indices p and b stand for a primary and back-up relay, respectively.

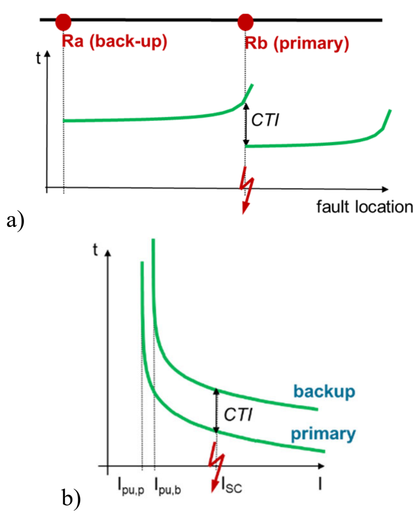

Fig.3. Definition of CTI for a relay pair: operating time vs. fault location (a) and current vs. operating time (b)

The relay pairs (RP) for the network configuration shown in Fig.2. are defined in Table II.

Table II. – Constants for IEC inverse curves

RP no.	Primary rel. no.	Backup rel. no.
1	2	1•
2	3	2
3	4	3
4	5	4
5	17	6•
6	18	17
7	19	18
8	20	19
9	7	8•
10	9	1•
11	9	20
12	10	5
13	10	6•
14	11	10
15	12	10
16	13	10
17	14	10
18	15	14
19	16	8•

The time delay and pick-up current settings of all relays were determined in a Differential Evolution (DE) [10] based optimization procedure, where T_{add} was set to 0. The applied objective function is given by (3):

$$\boldsymbol{T}_{\mathrm{opr}} = \sum_{\boldsymbol{r}=\mathbf{1}}^{\boldsymbol{N}_{\mathrm{RP}}}\left(\boldsymbol{t}_{\mathrm{p,r}} + \boldsymbol{t}_{\mathrm{b,r}}\right) + \boldsymbol{p} \tag{3}$$

where index r stands for the relay pair, N_{RP} denotes the number of all relay pairs, while p is the penalty. More details will be provided in the full paper.
The results presented in this paper were obtained for the protection system realization without the exchange of GOOSE messages. More details about the protection system realization are provided in [11], emphasizing the exchange of GOOSE messages.

3. Results

The closed-loop operation's performance with the proposed protection scheme is summarized in Table II, where the time, date, and location of the fault that appeared between individual relays (R) marked in Fig. 2 are given. The results show how many customers (Cust.) and transformers (Transf.) 20 kV/0.4 kV were without supply in the cases of faults when the proposed protection scheme, that fully supports permanent closed-loop operation and disconnects only the faulted line sections between relays were used. Moreover, the results also show how many customers and transformers 20 kV/0.4 kV would be without supply considering the same faults with the protection scheme used in the abandoned radial arrangement of feeders. The statistic related to the three events presented in Table III is shown in Tables IV.

Table III. – Fault events in the first half of 2019 in the discussed distribution network

Time of event	Location between	Disconnected			
		Loop configuration		Radial configuration	
		Cust.	Transf.	Cust.	Transf.
25.3.2019 at 19:00	(R4, R18) – (R3, R19)	49	4	2124	80
26.04.2019 at 16:53	(R4, R18) – (R3,R19)	49	4	2124	80
20.5.2019 at 07:52	(R6) – (R10) – (R5,R17)	1966	75	2588	103

Table IV. – Statistics of events presented in Table III

Event	Interrupted customers		Duration of interruption (min)	
	Closed-loop	Radial	Closed-loop	Radial
1	49	2124	23	-
2	49	2124	60	-
3	1966	2588	356	-

Considering definitions for SAIFI (System Average Interruption Frequency Index) and SAIDI (System Average Interruption Duration Index)

$$SAIFI = \frac{\text{total number of interruptions for a group of customers}}{\text{number of all customers}}$$

$$SAIDI = \frac{\text{total duration of interruptions for a group of customers}}{\text{number of all customers}}$$

the results presented in Table V are obtained.

Table V. – Calculated SAIFI and SAIDI (CL=closed-loop, Rad=radial)

Event	SAIFI			SAIDI (min)		
	CL	Rad.	Change (%)	CL	Rad.	Change (%)
1	0.023	1	**98**	0.53	23	**98**
2	0.023	1	**98**	1.38	60	**98**
3	0.76	1	**24**	270.56	356	**24**
1+2+3	0.81	3	**73**	272.5	439	**38**

Let us extend the interval of our observation to the last five years. Tables VI to X show the statistic of outages in the discussed network between years 2016 and 2020. The results presented in Tables VI to VIII are given for the years 2016 to 2018, before the permanent closed-loop was implemented. The results presented in Tables IX and X are provided for 2019 and 2020 after the implementation of the closed-loop operation. Based on the results presented, it is evident that the implementation of permanent closed-loop operation cannot reduce the number of events that lead to the outages. However, it can substantially reduce the duration of outages. In the given case, the permanent closed-loop operation decreased the average yearly duration of outages per customer from 329 min/customer to 111 min/customer. The presented data include the outages caused by faults as well as the outages caused due to maintenance. Although the users are without a power supply, the last ones are usually not included in SAIDI.

Table VI. Outages in 2016 (Out = Outage; All = All Customers; Aff = Affected Customers, Dur =Duration)

Out	Aff	Dur [min]	Aff/All	Dur* (Aff/All)	All
1	477	92.00	0.581	53.452	821
2	184	1.02	0.224	0.228	821
3	184	5.00	0.224	1.121	821
4	477	248.00	0.581	144.088	821
5	344	37.00	0.419	15.503	821
6	821	0.92	1.000	0.917	821
7	821	0.05	1.000	0.050	821
8	821	1.00	1.000	1.000	821
9	177	143.00	0.216	30.829	821
10	76	0.38	0.036	0.014	2137
11	76	0.22	0.036	0.008	2137
12	76	1.57	0.036	0.056	2137
13	2137	1.22	1.000	1.217	2137
14	1976	5.90	0.925	5.455	2137
15	1320	13.42	0.618	8.287	2137
16	45	243.68	0.021	5.131	2137
17	2137	31.28	1.000	31.283	2137
18	2137	39.00	1.000	39.000	2137
19	76	133.95	0.036	4.764	2137
20	23	299.00	0.011	3.218	2137
21	2137	0.60	1.000	0.600	2137
22	2137	0.78	1.000	0.783	2137
23	1968	0.28	0.921	0.261	2137
Total [min/(customer year)]				347.265	

Table VII. Outages in 2017 (Out = Outage; All = All Customers; Aff = Affected Customers, Dur =Duration)

Out	Aff	Dur [min]	Aff/All	Dur* (Aff/All)	All
1	183	2.95	0.223	0.657	822
2	183	1.50	0.223	0.334	822
3	822	1.27	1.000	1.267	822
4	822	1.25	1.000	1.250	822
5	79	11.20	0.037	0.413	2140
6	78	0.95	0.036	0.035	2140
7	78	1.87	0.036	0.068	2140
8	361	93.77	0.169	15.818	2140
9	2140	0.45	1.000	0.450	2140
10	2140	0.33	1.000	0.333	2140
11	427	2.08	0.200	0.416	2140
12	118	0.55	0.055	0.030	2140
13	1257	10.00	0.587	5.874	2140
14	24	56.78	0.011	0.637	2140
15	118	66.53	0.055	3.669	2140
16	88	235.72	0.041	9.693	2140
17	78	86.80	0.036	3.164	2140
18	78	14.27	0.036	0.520	2140
19	2140	5.05	1.000	5.050	2140
20	50	124.88	0.023	2.918	2140
21	24	95.25	0.011	1.068	2140
22	2140	3.65	1.000	3.650	2140
23	2140	1.20	1.000	1.200	2140
Total [min/(customer year)]				58.513	

4. Conclusion

The proposed paper deals with the permanent closed-loop operation as a measure for improving power supply reliability in rural medium voltage distribution networks. The proposed solution was implemented in the distribution network of Elektro Celje d.d., where permanent closed-loop operation started in January 2019. The power supply reliability has been improved by introducing additional switching devices with properly parameterized relays, which disconnect only the faulty section of the loop. In this way, a substantial improvement in power supply reliability has been improved substantially. The cost of its implementation was approximately 20 % of the cabling costs. Two years of operation clearly show that the applied solution did not reduce the number of outages, but it reduced their duration to 33% of the initial value (111 min vs 329 min per customer per year).

Table VIII. Outages in 2018 (Out = Outage; All = All Customers; Aff = Affected Customers, Dur =Duration)

Out	Aff	Dur [min]	Aff/All	Dur* (Aff/All)	All
1	484	190,35	0,587	111,672	825
2	341	14,48	0,413	5,986	825
3	484	84,37	0,587	49,495	825
4	825	8,58	1,000	8,583	825
5	825	190,62	1,000	190,617	825
6	183	764,28	0,222	169,532	825
7	2145	9,90	1,000	9,900	2145
8	2145	0,25	1,000	0,250	2145
9	1425	0,02	0,664	0,011	2145
10	2145	20,88	1,000	20,883	2145
11	149	31,37	0,069	2,179	2145
12	24	100,55	0,011	1,125	2145
13	24	1023,52	0,011	11,452	2145
14	78	1,63	0,036	0,059	2145
Total [min/(customer year)]				518.745	

Table IX. Outages in 2019 (Out = Outage; All = All Customers; Aff = Affected Customers, Dur =Duration)

Out	Aff	Dur [min]	Aff/All	Dur* (Aff/All)	All
1	43	12.48	0.050	0.630	852
2	852	2.37	1.000	2.370	852
3	293	0.00	0.344	0.000	852
4	27	578.35	0.032	18.328	852
5	267	59.10	0.313	18.521	852
6	852	5.67	1.000	5.667	852
7	1282	2.28	1.505	3.436	852
8	792	0.32	0.930	0.294	852
9	451	24.77	0.529	13.110	852
10	46	49.35	0.054	2.664	852
11	293	2.07	0.344	0.711	852
12	50	23.28	0.023	0.543	2145
13	24	187.47	0.011	2.098	2145
14	50	60.62	0.023	1.413	2145
15	26	71.08	0.012	0.862	2145
16	138	60.58	0.064	3.898	2145
17	26	163.07	0.012	1.977	2145
18	91	129.72	0.042	5.503	2145
19	26	256.45	0.012	3.108	2145
20	1984	0.80	0.925	0.740	2145
21	2123	5.95	0.990	5.889	2145
22	163	35.63	0.076	2.708	2145
23	2123	13.37	0.990	13.230	2145
24	79	259.27	0.037	9.549	2145
25	44	404.42	0.021	8.296	2145
26	79	1.57	0.037	0.058	2145
27	88	4.90	0.041	0.201	2145
28	1959	5.60	0.913	5.114	2145
Total [min/(customer year)]				130.915	

Table X. Outages in 2020 (Out = Outage; All = All Customers; Aff = Affected Customers, Dur =Duration)

Out	Aff	Dur [min]	Aff/All	Dur* (Aff/All)	All
1	24	1.00	0.029	0.029	840
2	467	0.93	0.556	0.519	840
3	409	1.73	0.487	0.844	840
4	120	2.53	0.143	0.362	840
5	119	2.80	0.142	0.397	840
6	840	5.60	1.000	5.600	840
7	540	13.88	0.643	8.925	840
8	60	302.88	0.071	21.635	840
9	24	57.05	0.029	1.630	840
10	80	26.80	0.037	1.000	2145
11	44	118.67	0.021	2.434	2145
12	80	943.37	0.037	35.184	2145
13	44	136.35	0.021	2.797	2145
14	44	38.15	0.021	0.783	2145
15	44	15.40	0.021	0.316	2145
16	26	1.00	0.012	0.012	2145
17	2096	2.50	0.977	2.443	2145
18	110	12.98	0.051	0.666	2145
19	26	0.52	0.012	0.006	2145
20	140	44.02	0.065	2.873	2145
21	166	29.33	0.077	2.270	2145
22	26	110.67	0.012	1.341	2145
Total [min/(customer year)]				92.064	

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