International Conference on Condition Monitoring, Diagnosis and Maintenance 2015
CMDM 2015 (3rd edition)
Athénée Palace Hilton Hotel, Bucharest, Romania, October 5th -8th, 2015

No. 128

Distribution Network Reliability and Asset Management

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SUMMARY

A program called DISPO ("distribution reliability") for power system analysis was developed in Croatian Distribution System Operator Company (HEP-ODS). Its main goal is to gather data such as transformer or line outages (statistics of operation events) and to produce reports based on this data. This paper uses gathered data for reliability indices calculation such as System Average Interference Frequency Index (SAIFI), System Average Interference Duration Index (SAIDI) and Customer Average Interference Duration Index (CAIDI). The thorough model of one distribution area that incorporates above-mentioned data form DISPO is developed using power system analysis software NEPLAN. Methodology for reliability indices calculation in NEPLAN is described and used on developed network model. Reliability analyses is part of distribution network optimization and planning process, so the whole process is explained for better understanding. Numerous load point (average failure rate, average outage time, average annual outage time etc.) and system reliability indices (SAIDI, SAIFI, CAIDI etc.) are calculated using NEPLAN for feeders, substations and distribution area. Energy Not Supplied (ENS) is also calculated and analyzed. Possible network improvements such as new interconnection points between feeders or automatization of disconnect switches for feeders' reliability increase are simulated and described. Finally, detailed asset management for observed area is formed and combined with reliability analyses. Main goal is to show on a realistic network model how statistics of operational events contribute to distribution network optimization and planning and how proper network planning can increase availability of distribution network.

KEYWORDS

Distribution network – Reliability analyses – Reliability indices – Power supply.

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1. INTRODUCTION

The general definition of reliability in engineering is the ability of a system or component to perform its required functions under stated conditions for a specified period. In power systems operation and planning reliability mostly means maintaining the continuity of energy supply to the customers. As continuity of supply is their basic task, power systems were designed to overcome possible outages and failures in a manner that customers can conduct their daily activities even during contingency events. Since investing in generation units and transmission grids is capital intensive, requires long term planning and their unavailability means energy supply interruption for a large number of customers, they were the targets of reliability analyses in the past. Nowadays, due to the rapid increase in energy demand and primary energy prices, when efficient system operation is imperative the focus of reliability analyses is relocating to distribution networks, as they became the most vulnerable part of power system. In other words, not sufficient amount of investments is being poured into the system and the grid is ageing. More than 90% of all customer reliability issues and costs occurs in distribution system so it is of essential value to design reliable distribution networks, [1] and [2]. Electric power systems are experiencing tremendous structural and regulation transformations from horizontally integrated entities (monopoles) to vertically structured competitive environment where electric power consumers can choose their supplier based on cost-effectiveness and reliability. In order to withhold their current consumers and to attract new, electric power utilities must ensure unobstructed power supply and reduce costs which eventually leads to the increase of profit and to sustainable operation. Interesting survey [3] was conducted in the US on large number of energy users where key drivers for customers loyalty were identified as: price, reliability, power quality and complaint handling. Important finding was that increase in reliability performances does not guarantee improved loyalty whereas decrease would be disastrous. Another important issue is that modern electricity appliances (loads) such as computers are very sensitive to energy supply interruptions and low power quality.

This paper will provide detail insight into reliability analyses as part of distribution network planning in Croatia. Used software for calculations is NEPLAN – software for planning and optimization of electrical networks [4]. More information about reliability analyses and NEPLAN could be found in [5] and [6]. A comparison of different softwares for reliability analyses is provided in [7]. The developed detailed model of the observed distribution network is used to analyze the reliability of a specific distribution network as part of distribution network optimization and planning. Real data is taken into account and possible improvement from all the new technologies is considered (distant breaking operations, smart reconfiguration of the network etc.).

2. RELIABILITY IN DISTRIBUTION NETWORKS

There are many different definitions, classifications and metrics for reliability in distribution networks in existing literature, here we will use explanations provided in [8]. Definition of reliability of distribution network used in this paper is classified as availability of power supply as part of power quality. Power quality could be seen from the utility point-of-view and customer-point-of-view (perceived power quality). From the utilities point-of-view power quality is divided into three categories:

- Commercial power quality,
- Availability of power supply,
- Waveform power quality,

and from the customers point-of-view into two categories:

- Reliability of customers installation, and
- Capability level of the customers' apparatus.

There are three main categories of reliability indices, [7] and [9], global indices or load point indices calculated for every modelled load and used for system indices calculation:

- Average failure rate (frequency of supply interruptions, F),
- Average outage time (mean interruption durations, T),
- Average annual outage time (probability of supply interruptions, Q);

Second category are system indices, calculated for groups of loads (feeders, areas, zones or whole distribution system):

- SAIFI - System Average Interference Frequency Index,
- SAIDI - System Average Interference Duration Index
- CAIDI Customer Average Interference Duration Index,

Third category are power and energy oriented indices, calculated for both single loads and groups of loads:

- W – Energy Not Supplied (ENS),
- P – Peak power not supplied.

Later in the paper, load point indices will be displayed on distribution network figures exported from NEPLAN close to loads they are referring to, system indices will be listed in tables for feeders and distribution areas, and power and energy indices are presented both on NEPLAN figures for loads and in tables for groups of load. The summary of the results and their impact on future investments and network planning is also given.

3. DISTRIBUTION NETWORK OPTIMIZATION AND PLANNING

Croatian distribution system consists of 21 distribution area and is geographically allocated. In this paper distribution area Virovitica is used as case study for reliability analyses. Structure of distribution system is as follows (number in parenthesis refers to number of such substations in distribution area Virovitica):

- 110/35 kV substations (2);
- 35 kV network;
- 35/10 kV substations (8),
- 10 kV network,
- 10/0.4 kV substations (500).

100 kV network is part of transmission system and it is not part of this research. 0.4 kV network is considered as low voltage network. Low voltage network characteristics are included in substations 10/0.4 kV with realized peak power and number of customers and additionally all the large customers (above 100 kW) modeled with their exact load curves. National strategy for distribution network development in Croatia includes gradual transition from 110-35-10-0.4 kV system to 110-20-0.4 kV system, but distribution area of Virovitica is still at the beginning of the process with the more intense transition being the long term plan.

To ensure satisfactory grid operation and development constant observation and analysis of operation and development planning is required. Therefore, in order to maintain the quality of distribution service, planning process includes several steps:

- Load flow analyses in normal operating state – loadings (lines and transformers) and voltages (nodes) are main trigger for distribution system investments;
- Reliability analyses:
  - Load flow analyses in emergency operating state, (N-1) criterion – manually disconnecting 35 kV equipment (35/X kV transformers and 35 kV lines) in order to observe system's behavior in emergency operating state; loadings (lines and transformers) and voltages (nodes) in such state are important trigger for distribution system investments;
  - 10(20) kV grid reliability indices analyses – system reliability indices are considered as one of the triggers for the distribution system investments;
- Economic justification for grid investments:
  - Load flow analyses in normal operating state: power losses;
  - Load flow analyses with load profiles in normal operating state: energy losses;
  - Reliability analyses, 10(20) kV grid reliability indices: unsupplied power and energy;
  - Losses and unsupplied energy and power are considered as one of the triggers for the distribution system investments;
- Asset management – equipment age should not exceed its life expectancy, trigger for investments;
- One medium voltage level distribution system strategy – if required conditions are achieved parts of distribution system should realize transition from 110-35-10-0.4 kV system to 110-20-0.4 kV system.

Reliability analyses is performed in two stages. First one includes manual disconnection of grid elements (transformers and lines) and observation of system's behavior in emergency operating state. Mentioned detailed analyses is possible to perform just in 35 kV networks where smaller number of elements exist. In 10 kV network, with a lot more elements, such analyses is too time-consuming so reliability analyses is performed as calculation of reliability indices in NEPLAN. Eventhough it is still not the case in Croatia, there are cases where suppliers refund household customers if the rate and length of outages exceed predefined limits. Grid maintenance has become more challenging and frequent monitoring and diagnostics are required since it is not acceptable for the customers to stay without electricity even for a short period. Absence of proper maintenance is potentially harmful and eventually leads to bigger problems. So it is of key importance, especially in radial rural networks, to ensure alternative supply lines. Such investment justification is closely linked with the improvements of reliability indices that are used to identify critical network feeders.

Distribution network planning described above is performed for present year and for future projections with justified investments and network modifications. Consumption increase, both in households and in industry customers, is included in future projections alongside the new grid elements (lines, substations, circuit breakers, disconnect switches etc.) and modifications in grid topology that is also being optimized. As last part of distribution system optimization and planning all above described analyses are considered and overlapped to create investment plan for long term distribution system development.

Next chapter will provide explanation of reliability indices calculation methodology for 10 kV network for long outages (>3min). Afterwards, system reliability indices analyses will be performed on several different data sets:

- data set based on historical data,
- data set based on present grid state modelled in NEPLAN,
- data set derived from future states of grid also in NEPLAN.

4. RELIABILITY INDICES ANALYSIS

Apart from input data necessary for load flow analyses (substation and line data) reliability indices analyses requires the following:

- Number of customers served on each substation 10/0.4 kV,
- Average element failure rate,
- Average element outage time (or average time needed to repair affected element),
- Location of circuit breakers (CB) and disconnect switches (DS),
- Feeders interconnections,
- Average required time for switching operations (manual or automatic),
- Allowable limits of loadings and voltages during emergency operating state.

Exact number of customers is entered for each 10/0.4 kV substation. Standard failure rates and element outage times are assigned to each 10 kV line as listed in table (Table 1). Substations, CB and DS are considered as ideal elements (which assumes that device will function ideally since no sufficient data was available to model and empirical data shows the reliability of these devices is quite high). CB and DS are drawn on their exact location as in the real network. Required time for switching operations of manually operated DS is 60 min, and for automatically operated CB is 10 min.

Table 1 Standard element failure rates and outage times

Grid element	Average element failure rate (f/km·year)	Average element outage time (min)
Cables	0.07	960
Lines	0.14	300

Required standards for system reliability indices in Croatian Distribution System Operator (DSO) are listed in table (Table 2).

Table 2 System reliability indices standards in Croatian DSO

Standards	Network type	SAIDI (min/year)	SAIFI (failure/year)
Standard 1	Urban areas with mostly cable network	120	2
Standard 2	Suburban areas and bigger settlements	240	4
Standard 3	Overhead lines in rural areas	360	8
Additional global criterion		Retaining present state if it is better than standard	

4.1. Realized system reliability indices

Realized system indices are calculated based on historical data provided by DSO (Table 3) for the whole distribution area. This data will be used in next chapter to compare with those obtained from NEPLAN calculations. Cells in table (Table 3) are colored in accordance with satisfied standard:

- Satisfied standard 1 – light green;

- Satisfied standard 2 – dark green;
- Satisfied standard 3 – yellow;
- None of the standards satisfied – red.

While observing table (Table 3) it could be concluded that in average distribution area as a whole satisfies standard 3 for SAIFI and standard 1 for SAIDI.

Table 3 Achieved system reliability indices

	Year	ENS (MWh)	SAIDI (min/year)	SAIFI (failure/year)	CAIDI (SAIDI/SAIFI)
Distribution area Virovitica	2010.	27,64	324,64	1,22	267,08
	2011.	18,35	89,10	0,77	115,14
	2012.	34,29	390,98	1,13	346,02
	2013.	38,18	231,33	0,86	270,54
	2014.	28,73	188,02	0,97	193,93
	Average	29,44	250,93	0,99	253,78

4.2. Calculated system reliability indices – present state

Entire network of distribution area Virovitica is modelled in NEPLAN with above described assumptions and observed part of it is displayed in Figure 1. There are 8 substations 35/10 kV and more than 50 10 kV feeders in observed distribution area, but because of conciseness of the paper table (Table 4) lists system reliability indices just for two 35/10 kV substations and their 10 kV feeders for the present state (which will be latter used as a reference). Considering lack of data and assumptions mentioned above in text, it can be seen that results obtained from the model match those from Table 3 very well, 15% difference is noticeable in SAIDI and 42% difference in SAIFI. Green color of cells in last column indicates that both SAIFI and SAIDI satisfy required standard, while red indicates the opposite. Load point indices for two 10/0.4 kV substations of feeder "Bistrica" are shown at Figure 2 and Figure 3 for different scenarios observed.

Table 4 Calculated reliability indices for present state

Area/Feeder	ENS (MWh)	SAIDI (min/year)	SAIFI (failure/year)	CAIDI (SAIDI/SAIFI)	Standard
Centar	0,74	27,83	0,22	124,26	1
Industrija	0,10	7,36	0,09	80,03	1
Limex	0,09	6,91	0,12	60,10	1
Mikleuš	6,90	504,45	2,13	237,28	3
Radosavci	2,29	313,01	1,40	222,94	3
Slatina Istok	0,26	24,28	0,22	110,89	1
Slatina Zapad (Slatina I)	0,80	42,62	0,27	155,55	2
35/10 kV substation Slatina I	**11,33**	**128,21**	**0,64**	**200,02**	**2**
Bistrica	2,88	472,86	1,48	318,64	3
Čađavica	11,54	456,52	2,34	194,84	3
Gornji Miholjac	5,99	619,19	2,50	248,07	3
Kapinci	2,88	294,98	2,29	128,92	3
Medinci vodovod	0,73	209,37	0,94	223,44	2
Spojni vod	0,05	44,58	0,12	374,61	1
35/10 kV substation Slatina II	**21,19**	**432,66**	**2,27**	**190,27**	**3**
Distribution area Virovitica	**114,43**	**271,33**	**1,41**	**192,43**	**3**

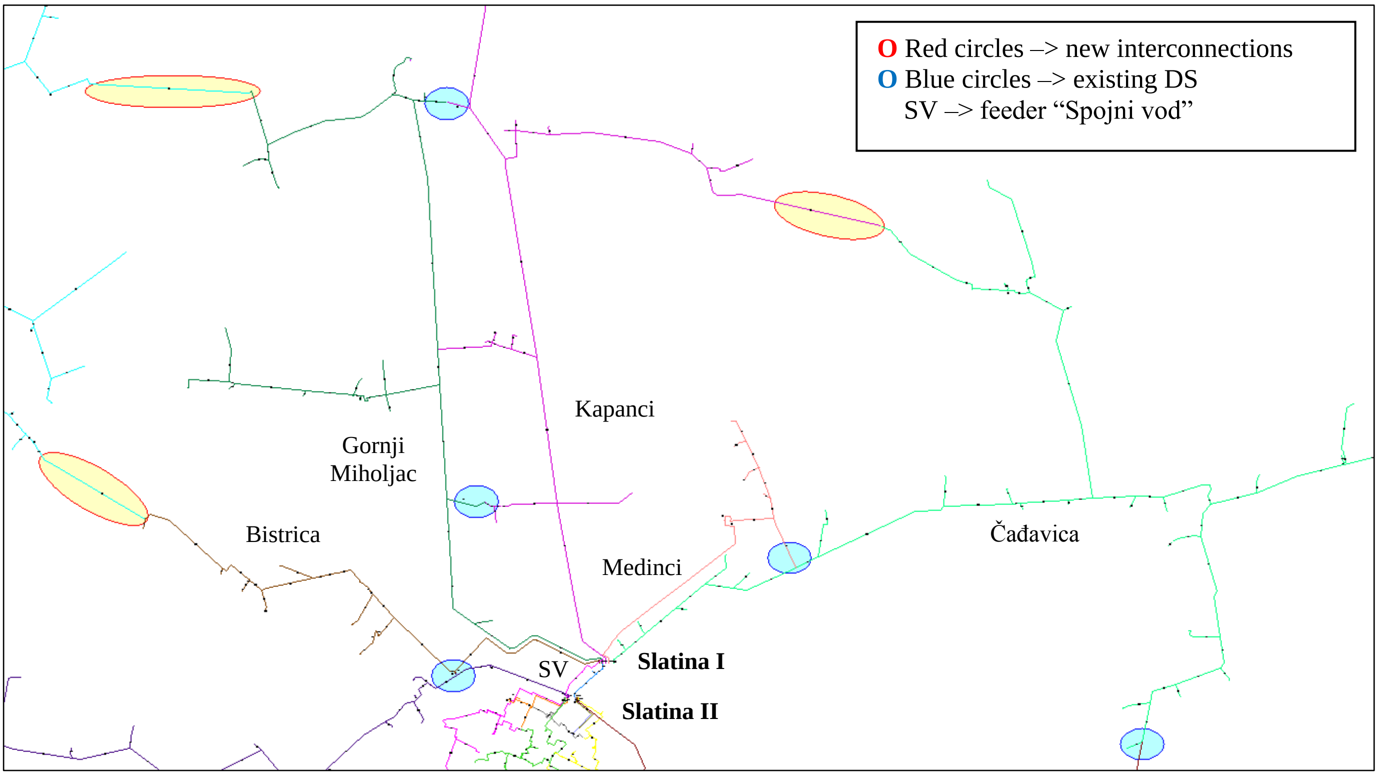

Figure 1 Observed part of distribution area Virovitica

Feeders with long mostly overhead lines with small number of interconnection have very high reliability indices (for example 10 kV feeder "Gornji Miholjac"), which means they are very unreliable. On the other hand, feeders with short cables have very low reliability indices (for example 10 kV feeder "Slatina istok") meaning they are very reliable. Main reasons for insufficient reliability indices are summarized as follows:

- Feeder length,
- Percentage of overhead lines,
- Number and position of switching devices (CB, DS etc.),
- Rate of automatization,
- Rate of interconnections between feeders,
- Climate and geographic factors,
- Customer density,
- Distribution elements' loadings and voltages,
- Adequacy of maintenance and diagnostics of distribution elements.

4.3. Calculated system reliability indices – future state

Possible strategies and actions for reliability increase are listed in Table 5. Int this paper three different future grid states will be presented: future grid with new interconnection points, future grid with new interconnection points and automatization of DS and future grid with replaced old elements. Within those future states of grid three different actions (one from each strategy) form Table 5 are considered: proper asset management, distribution network automatization and reconfiguration of distribution network topology (new interconnection lines between feeders). Because of its poor reliability 35/10 kV substation Slatina I along with its 10 kV feeder is chosen as representative for reliability increase.

Introducing new interconnection lines between feeders (red circles on Figure 1) decreases SAIDI index and ENS because separated area during failure have new alternative way for power supplay. It can be seen from Table 6 that feeder "Bistrica" is now in green zone, i.e. required standards are satisfied. Although, SAIDI is decreased for feeders "Čađavica" and "Gornji Miholjac" they are still in red zone. Right part of Figure 2 also indicates that reliability has increased. Mean interruption duration (T) and probability of supply interruptions (Q) has decreased by 80 %.

Table 5 Strategies and actions for increased reliability of distribution networks

Strategies	Actions
Reduction of number of faults	Preventive maintenance
	Monitoring critical elements
	Proper asset management (replacement of spent equipment)
	Upkeep of elements surroundings (vegetation…)
	Protection against human or animal contacts with elements
Reduction of time of interruption	Distribution network automatization
	Network topology modification while in emergency state
	Faster fault detection
	Faster crew response (both for repair of affected elements and for manual operation of switching devices)
Reduction of number of affected customers	Reconfiguration of distribution network topology
	More protective and switching devices
	Resonant transformer grounding

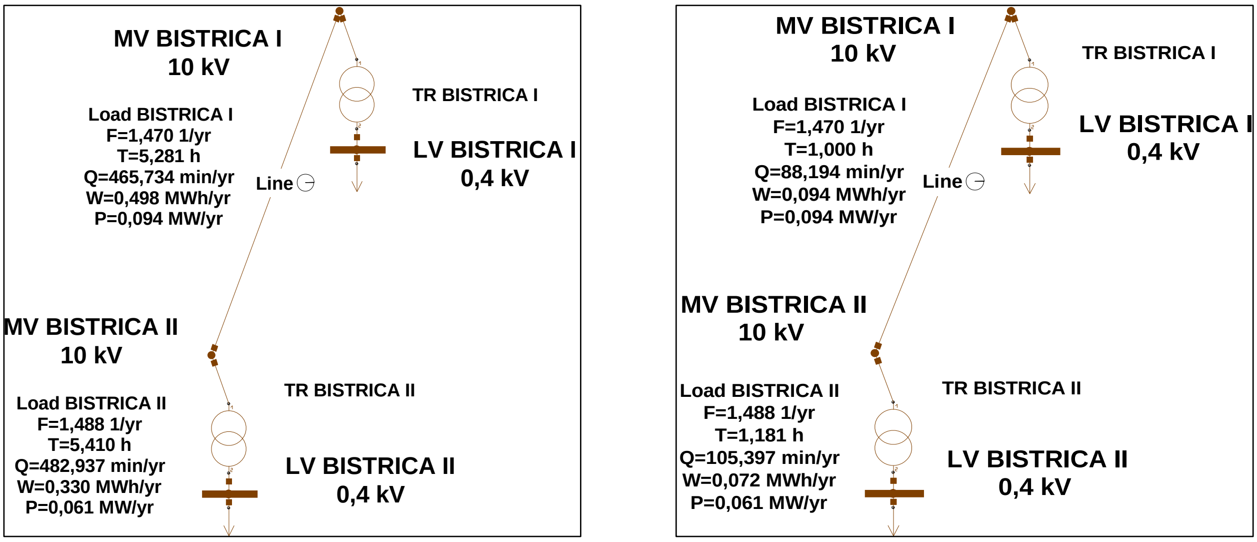

Figure 2 Load point indices of two 10/0.4 kV substations, end of feeder Bistrica (left figure is for present state, while right is for future state with new connection points)

Table 6 Calculated reliability indices for future state – new interconnection points

Area/Feeder	ENS (MWh)	SAIDI (min/year)	SAIFI (failure/year)	CAIDI (SAIDI/SAIFI)	Standard
Bistrica	1,73	252,39	1,48	170,07	3
Čađavica	7,57	389,48	2,58	150,84	3
Gornji Miholjac	5,39	553,15	2,50	221,61	3
Kapinci	2,59	265,06	2,29	115,85	3
Medinci vodovod	0,73	209,37	0,94	223,44	2
Spojni vod	0,05	44,58	0,12	374,61	1
35/10 kV substation Slatina II	**18,05**	**365,09**	**2,27**	160,55	3
Distribution area Virovitica	**110,76**	**261,91**	**1,41**	185,75	3

In order to further increase reliability, DS on all new interconnection lines and few existing DS between feeders (blue circles on Figure 1) are modified to remote control (they used to be manually operated). As it can be observed from Table 7, reliability indices decreased. Again only ENS and SAIDI decreased because automatization doesn't reduce the number of failures just duration of switching operation. But still feeder "Gornji Miholjac" does not satisfy required standard. The only ways how to decrease SAIDI more are faster fault detection and quicker crew response, but this cannot be conducted by technical improvments so it is not simulated in this paper. Load point indices (T and Q on left part of Figure 3) on observed 10/0.4 kV substations are decreased by additional 17% (97% decrease in total).

Table 7 Calculated reliability indices for future state – automatization of disconnect switches

Area/Feeder	ENS (MWh)	SAIDI (min/year)	SAIFI (failure/year)	CAIDI (SAIDI/SAIFI)	Standard
Bistrica	1,50	208,95	1,48	140,80	3
Čađavica	5,52	307,23	2,58	118,99	3
Gornji Miholjac	5,28	509,84	2,50	204,26	3
Kapinci	1,98	202,67	2,29	88,58	3
Medinci vodovod	0,60	194,03	0,94	207,07	2
Spojni vod	0,05	44,58	0,12	374,61	1
35/10 kV substation Slatina II	**14,63**	**304,11**	**2,27**	133,73	3
Distribution area Virovitica	**106,98**	**253,54**	**1,41**	179,81	3

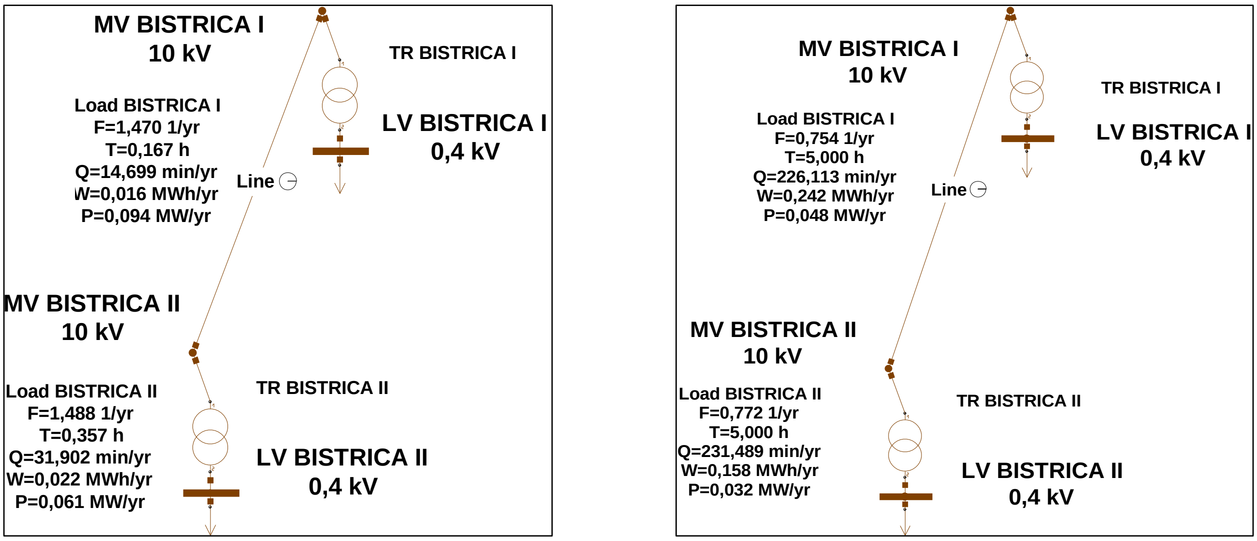

Figure 3 Load point indices of two 10/0.4 kV substation, end of feeder Bistrica (left figure is for future state with automatization of switches, while right is for future state with replaced old overhead line sections)

4.4. Distribution network reliability increase with proper asset management

As an example of distribution network reliability increase using asset management, feeder "Bistrica" is chosen due to its very old overhead line's sections. Most of the sections is older than 48 years (66.7%) and more than 96% of sections are older than 38 years (Figure 4). If those parts are replaced with new sections, SAIDI would decrease by 51.5% and SAIFI by 48.6% in regard to the present state of the grid (Table 4).

Table 8 Calculated reliability indices for future state – replacement of old equipement

Area/Feeder	ENS (MWh)	SAIDI (min/year)	SAIFI (failure/year)	CAIDI (SAIDI/SAIFI)	Standard
Bistrica	1,40	228,89	0,76	299,99	3

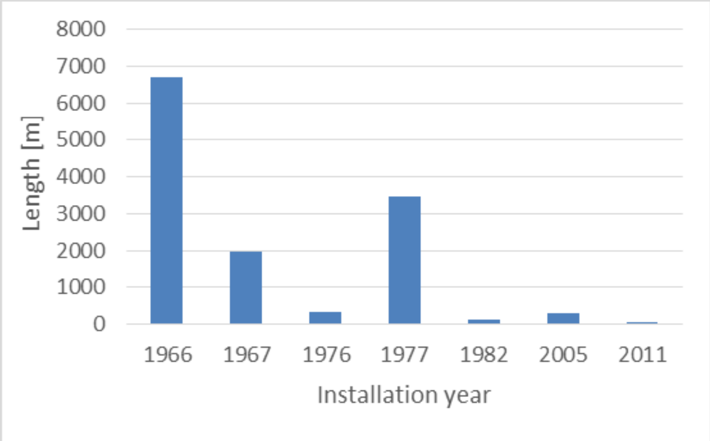

Figure 4 Feeder "Bistrica", overhead lines age distribution

5. CONCLUSION

Reliability of distribution networks is an important part of distribution system planning and optimization. Systematic and justified investment in new switching devices and gradual automatization improves networks ability to supply high number of customers even in emergency operating state. Along with such improvements, continuous monitoring and diagnostics of grid elements and replacement of old and unreliable equipment can further increase system's reliability. Proper asset management combined with reliability analyses is required to maintain sufficient reliability standards.
Analyses as those provided in this paper will become more and more important as customers (along with their appliances) are becoming more sensitive to power quality and supply interruptions and as customer density increases.

6. ACKNOWLEDGEMENT

The work of the authors is a part of the FENISG- Flexible Energy Nodes in Low Carbon Smart Grid funded by Croatian Science Foundation under project grant No. 7766.

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