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Improved Procedures of Distribution Power Network Failure Data Collection for Supply Availability Index Evaluation

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Distribution network data archiving, editing and storing are permanent activities of high importance, obligated by legislation. The paper describes improved methods for the distribution`s power system fault data collection in the form of new developed components of operational database. The Visual Basic Code solution was developed to ease faults data input, data filtering, and for data processing. After a monitoring period of almost 3 years, reliability indices of the 35 kV network in Elektra Slavonski Brod were evaluated. The methods could be applied to other distribution power systems as well.

Poboljšani postupci za prikupljanje podataka o zastojima u distribucijskoj elektroenergetskoj mreži za izračunavanje pokazatelja raspoloživosti opskrbe

Izvornoznanstveni članak

Arhiviranje, obrada i čuvanje podataka o radu distributivne mreže kontinuirane su aktivnosti od velike važnosti, predviđene i zakonskom regulativom kao obvezne. Članak opisuje poboljšane postupke za prikupljanje podataka o kvarovima u distribucijskom elektroenergetskom sustavu u obliku novo razvijene baze podataka o funkciji komponenta sustava. Programom razvijenim u Visual Basicu omogućeno je lakše unošenje podataka, i dobivanje točno određenih podataka i njihovih obrada. Nakon perioda praćenja kvarova primjenom predložene metode u trajanju od skoro 3 godine, izračunati su pokazatelji pouzdanosti za 35 kV mrežu Elektre Slavonski Brod. Predložene metode mogu se primijeniti i na ostalim distributivnim elektroenergetskim sustavima.

1. Introduction

Electric power supply reliability is one of the most important input parameters of all other global economy areas regarding the social economic benefit and at the same time it also ensures a normal way of living to people in their homes. Electric power supply network consists of three main systems: production, transmission and distribution. Transmission, and particularly distribution networks are exceptionally complex structures, with a great number of components and miles of power lines connected together, which makes it possible to get electric energy to all end users. Since the electric power network is composed of an enormous number of mechanical and electrical integral parts, failure of just one part could be sufficient to cause interruptions in the power supply with considerable financial loss.

Therefore, the basic function of the power system is a reliable and secure supply to all customers with at least prescribed electric power quality according to EN 50160. Based on decades of the power system, engineers acquired experience in more than 90 % of all failures which cause interruptions in the power supply the failure of components in the distribution power subsystem [9]. The main reason for this is the significant lengths of distribution overhead and buried power lines and great number of distribution transformer substations. The electric power network is composed of a great number of mechanical and electrical components which can be replaced when a fault occurs or even during the maintenance process (periodic maintenance or when any component parameter deviates outside of regulated range).

Symbols/Oznake

$AENS$	- Average Energy Not Supplied Index - indeks prosječno neisporučene energije
$AENS$	- Average Energy Not Supplied Index, MWh/customer - indeks neisporučene energije po kupcu
$ASAI$	- Average Service Availability Index - indeks prosječne raspoloživosti napajanja
AvC_{um}	- average of cumulative product, min/failure - prosječni kumulativni produkt broja kupaca bez opskrbe i vremena trajanja kvara po kvaru
$AvT_{\mathrm{fault/fault}}$	- average time fault period per failure - prosječno vrijeme trajanja kvara po kvaru
$AvT_{\mathrm{location/fault}}$	- average time location period per failure - prosječno vrijeme trajanja lokacije kvara po kvaru
$AvT_{\mathrm{reaction/fault}}$	- average time reaction period per failure - prosječno vrijeme trajanja reakcije na kvar po kvaru
AvTrepair/fault	- average time repair period per failure - prosječno vrijeme trajanja popravke kvara po kvaru
$BPECI$ (BP)	- Bulk Power Energy Curtailment Index - indeks količine neisporučene energije uslijed kvara po 1 MW
C_{um}	- cumulative product of unsupplied consumer's number and duration of failure - kumulativni produkt broja kupaca bez opskrbe i vremena trajanja kvara
D	- duration of load curtailment, h/year - trajanje perioda bez opskrbe
D_{d}	- duration (in number of days during the year) of estimated load level - trajanje procijenjene razine snage (u broju dana tijekom godine)
ENS	- total unsupplied energy, MWh - ukupna neisporučena energija
$ENSF$	- average unsupplied energy per failure, MWh/failure - prosječna neisporučena energija po kvaru
$ENSY$	- average unsupplied energy per year, MWh/year - prosječna neisporučena energija po godini
f	- frequency of load curtailment - frekvencija kvara
f_{i}	- frequency of supply interruptions to the node i - frekvencija prekida napajanja čvora i
I	- number of contingencies causing bus isolation - broj slučajeva s izolacijom sabirnica
l	- power line length - duljina kablova
L	- electric power load, MW - električna snaga tereta
L_i	- amount of average load connected to the node i - iznos prosječnog opterećenja priključenog u čvoru i
Lp	- peak maximum electric power load of the system - vršna snaga tereta sustava
$MTTF$	- mean time to failure, h - srednje vrijeme do kvara
$MTTR$	- mean time to repair, h - srednje vrijeme popravke
n_{i}	- number of consumers in bus i - broj kupaca napojenih iz čvora i
N	- number of failures in monitored time period - broj kvarova u vremenskom periodu promatranja
m	- number of years of monitored period - broj godina vremenskog perioda promatranja
P	- probability of load curtailment - vjerojatnost kvara
r	- average failure duration - prosječno trajanje kvara
r_{i}	- failure duration - vrijeme trajanja i-tog kvara
S	- number of contingencies causing split network - broj slučajeva s razdvajanjem sustava
$SAIDI$	- System Average Interruption Duration Index, hours - indeks prosječnog trajanja prekida sustava
$SAIFI$	- System Average Interruption Frequency Index - indeks prosječne učestalosti prekida sustava
T	- procentual period value of estimated load level duration during year - postotna vrijednost trajanja procijenjene razine opterećenja tijekom godine
T_{down}	- total down-time, min - ukupno vrijeme komponente u kvaru
T_{fault}	- time fault period - vrijeme trajanja kvara
T_{location}	- time location period - vrijeme trajanja lokacije kvara

T_{reaction}	- time reaction period - vrijeme trajanja reakcije na kvar	T_{up}	- total up-time - ukupno vrijeme komponente u radu
T_{repair}	- time repair period - vrijeme trajanja popravka kvara	λ	- failure rate - intenzitet kvara

Distribution subsystem engineering activities consist of analyzing and decision making in different directions to improve commercial results such as productivity improvment or loss reduction. To reach the best solution in any activity, managers need archive-data-described system operations in the past.

Maintenance of the distribution system to improve power quality (by improving voltage characteristics and decreasing the number and duration of interruptions); dispatching electric loads to the end users to reduce the power losses; system planning (by installing new buses and branches or replacing a present component with new greater transmission capacity) to enable the connection of new consumption are only some examples of engineers` activities in the distribution power system.

Reliability aspects of EN 50160 consist of the following variables: maximum allowed number of voltage interruption per year and maximum allowed duration of voltage interruption per year for each consumer. Here, the non voltage period starts when voltages drop under a level less 1 % than the nominal voltage level. Depending on consumer notification on exact non-voltage period (starting moment and duration), there are two possible interruptions: planned maintenance activity (when end users are properly informed by radio or newspaper several days before the interruption) and accident (unexpected) faults. The accident faults can be sorted in to two categories: long (permanent failure) and short interruptions (transient failure, duration is less than 3 minutes). Long interruptions should not exceed the frequency of occurrence of 10-50 per year. Short interruptions are expected to occur not more than several hundred times whilst interruption duration of 70 % should be less then 1 s.

Herein, for distribution system availability index evaluation non-voltage periods caused by maintenance activities are neglected and only those components failures which cause interruption of power supply to the consumers are the object of this approach.

To perform the calculation of power system availability indices, all basic parameters of each system existing component (electrical unit parameters with lengths and reliability parameters), load demands distribution in all buses and branches and topology of the system are required. Reliability parameters of each component of the distribution power network differs from each other by a number of deterministic (technical) and stochastic (operational) variables like age, length (for lines), location in system topology, type – overhead or buried line, radius and conductor material, isolation technology type, electrical line parameters, electrical soil parameters, perspective of the earth surface, nominal power, peak load, day/annual load curve, meteorological aspects etc. The exact mathematical expressions containing all the above variables used to calculate a component's reliability parameters does not exist in advance, unless it is possible to use archive data given by permanent monitoring of component operation all the time throughout the whole year (or even better more years).

Therefore, within the scope of the research, the component's operation database aims to store and analyze the monitored data and to calculate components' reliability parameters during any desired period in the past has been developed and the results will be presented in the following. The database is designed to enable the preparation of input data for availability evaluation in order to define the optimal power system operational state regarding the reliability aspect.

2. Availability parameters and indices

The distribution network's availability index evaluation is based on a well-known analytical [1] state enumeration method (using Markov state space model of power lines and transformers as system components), enumerating all possible components and power system states and composed of time-series of data on independent power system components failures and their coincidence of first, second and third level. Voltage existence at distribution network load nodes identifies system deficiencies, looking for all interruptions causing the outages. Markov state space model is based on exponential reliability function with invariable failure rate of components, usually used in power system reliability evaluation due to its simplicity.

2.1. Availability input parameters

Two basic branch parameters needed as input variables for reliability (availability) calculation are failure duration (r) and failure rate (λ). These parameters are not technical parameters defined by the manufacturer during the equipment design/testing phase; in fact they are caused by the component/system operation which is hardly predictable in its basis (failures, power flows, weather conditions, material depreciation, unexpected high consumption caused by deficit of other power source, human factor etc.)

Failure duration

Failure duration is calculated for each system branch (transformer and power line) as an average of cumulative - total failure duration, which in turn is calculated as the sum of hours of component failures per year. Here, N is the number of failures in a monitored time period of m years:

$$r = \frac{\sum_{i=1}^{N} r_i}{m}, \text{ hours/year.} \tag{1}$$

Failure rate

Failure rate is calculated on 100 km for the each power line as:

$$r = \frac{\sum_{i=1}^{N} r_i}{m}, \text{ 1/year, 100 km,} \tag{2}$$

where l is the power line length.

Failure rate of transformer is calculated as:

$$\lambda = \frac{N}{m(8760 - r)}, \text{ 1/year.} \tag{3}$$

2.2. Power quality (availability) output indices

The power system quality indices which are used to evaluate the availability aspect can be divided into several groups:

The number and type of supply interruption

Number of contingencies causing split network (S)

Number of contingencies causing bus isolation (I)

The load curtailment reliability indices

Probability of load curtailment (P-$\times 10^{-3}$)

Frequency of load curtailment (f-occurrence/year)

Duration of load curtailment (D-hours/year)

The Bulk Power Energy Curtailment Index (BPECI, BP)

BPECI shows quantity amount of unsupplied energy MWh per 1 MW peak load during the year. Usually, it is expressed in the system minutes – *SM* (by multiplying *BPECI* by 60). There are two interpretations: a) actual system malfunction index *SM* is presented on an equivalent power system interruption during peak load for so many system minutes and b) *SM* is duration of outage time per consumer at system peak load.

System reliability indices [1,6]:

a) *SAIFI*, System Average Interruption Frequency Index

$$SAIFI = \frac{\sum f_i n_i}{\sum n_i}, \frac{\text{interruption / prekida}}{\text{consumers, year / potrošač, godina}}, \tag{4}$$

b) *SAIDI*, System Average Interruption Duration Index

$$SAIDI = \frac{\sum D_i n_i}{\sum n_i}, \frac{\text{h}}{\text{consumers, year / pot., god.}}, \tag{5}$$

c) *ASAI*, Average Service Availability Index

$$ASAI = \frac{8760 \sum n_i - \sum D_i n_i}{8760 \sum n_i}, \tag{6}$$

d) *ENS*, Total Energy Not Supplied

$$ENS = \sum L_i D_i, \text{ MWh}, \tag{7}$$

e) *AENS*, Average Energy Not Supplied Index

$$AENS = \frac{\sum L_i D_i}{\sum n_i}, \frac{\text{MWh}}{\text{consumers, year / pot., god.}}, \tag{8}$$

e) *ENSY*, Energy Not Supplied per Year

$$ENSY = \frac{\sum L_i D_i}{m}, \frac{\text{MWh}}{\text{year / god.}}, \tag{9}$$

e) *ENSF*, Energy Not Supplied per Failure

$$ENSF = \frac{\sum L_i D_i}{N}, \frac{\text{MWh}}{\text{failure, year / kvar , god.}}. \tag{10}$$

3. Developed components operation database

3.1. Introduction

Distribution network data archiving, editing and storing are not only permanent activities of high importance, obligated by legislation (EN) but also very extensive pursuit.

Components operational database design is the first step in any kind of modern system analyzing. If the system manager wants to achieve effectiveness in system operation or to improve benchmarks in desired direction, he must become familiar with the power network. Distribution network is well described by topology (branches and buses), system states, input and output variables (demands, technical preconditions) and nowadays characteristics of deregulation and deregulated market. During a complete network analysis, distribution network activities (investments, dispatching, maintenance, and engineering), voltage problems, capacity deficiencies, branch overloads, disruption of electric power supply, power system splitting features and similar problems have to be well known. The usual approach for decision-making in complex distribution networks with insufficient data is objectively ineffective and a matter of the past due to modern power market principles.

Thus, designing a data base component function with all network data is a basic precondition to optimize everyday technical and financial requests. It is not often easy to see real benefits, especially during the occurrence of the fault because of the decision time deficiency. The real benefits of that process lie in easy and fast selection and filtering of some specific data that can lead to technical or managerial decision-making.

When the failure occurs in the distribution power network at higher voltage level - more electricity end-users are affected and consequently damages related to unsupplied energy are more important. Also, staff efficiency related to switching procedure selection, failure location and repair has to be of a higher quality. Therefore, several tools need to be designed and installed in order to ease the system state overview and to achieve the desired aim.

3.2. Main parts

Figure 1 on next page illustrates the developed components operational database with its tables and relationships. Data in tables are structured, interconnected, rapidly accessed, non redundant and sorted, describing events (failures, faults, maintenance), system states (switching states, failure type, failure cause) and objects (components, power lines and transformer substations).

The relation between two tables depends on the connection key determination, with its connection properties and rules. Here, the power system is well designed by two main (Power Line and Transformer Substation) and three helpful interrelated tables (Location of Power Line, Power Line Characteristic and Power System Components). Power system topology is described by tables Transformer Substation and table Power Line,

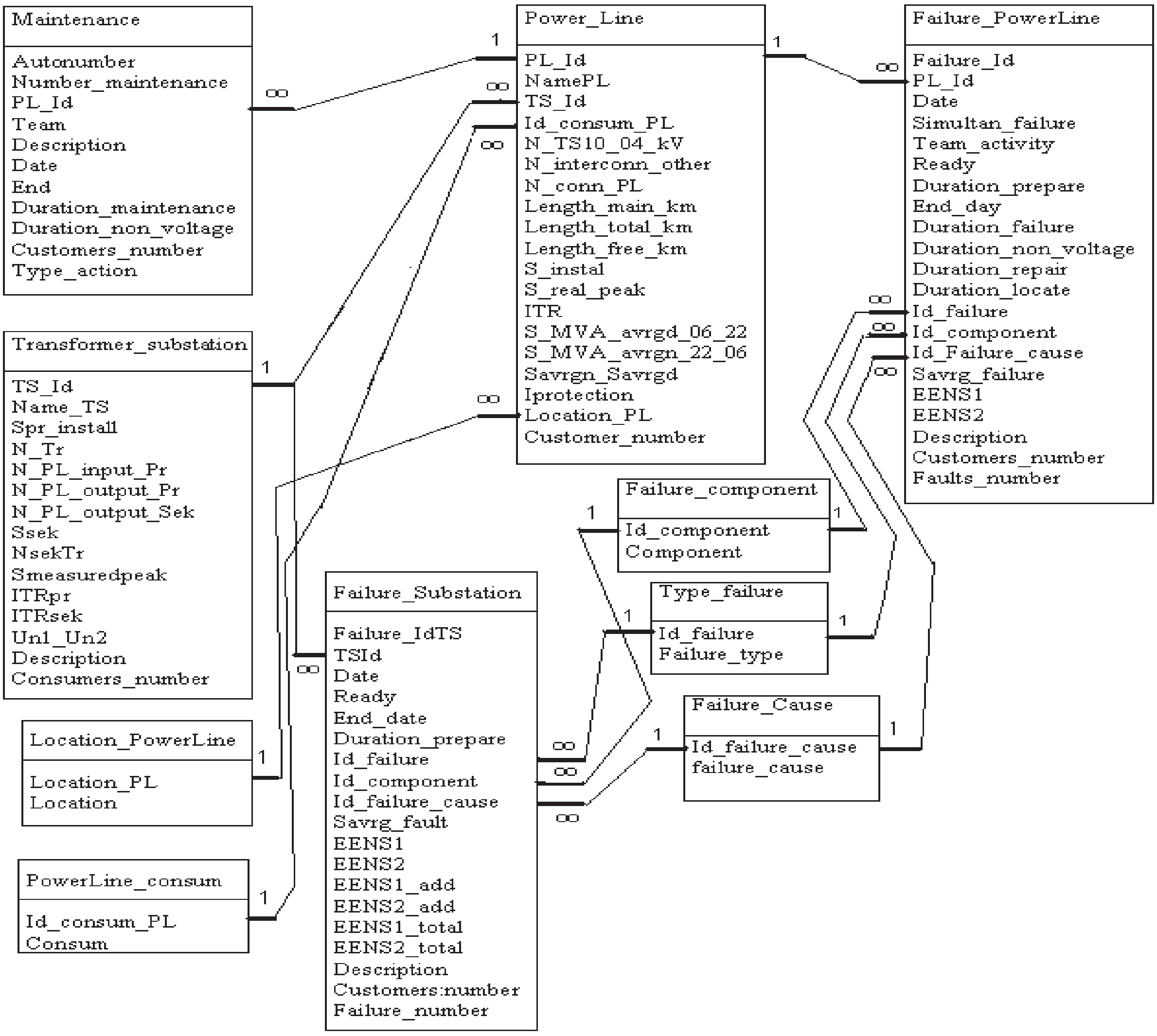

Figure 1. Relationships scheme between entities and objects in developed database

Slika 1. Shema veza entiteta i objekata u razvijenoj bazi podataka where any existing transformer substation is the incident feeding point for several power lines. Table *Power Line* is connected with tables *Power Line Consumers* and *Location Power Line* for better description of power line without unneeded repeating of similar data. *Failure Substation* is connected to a *Transformer Substation* where for each transformer substation there can be more zero failure records (if the fault never occurs in monitored period) up to an enormous number of possible failures. Each record of *Failure Substation* is better described by tables *Failure Cause*, *Failure Components* and *Type Failure*. It is very similar to table *Power Line Failures*. Table *Maintenance* is connected with table *Power Line* and *Failure component*.

The memory size of data base depends on the distribution network size itself and total time of system monitoring. The number of records in tables *Transformer Substation* and *Power Line* consists of as many records as there are components in the real distribution network. Adding a brand new component in the existing system and changing present branch connections are simple. The memory size of *Failure* and *Maintenance* tables depends on the power system area: present condition of network component and it is about 100-400 records (faults) per year in the analyzed network.

Table *Power Line Location* defines a variety of characteristic demand load shape (like urban households, rural households, farms, industry etc.), which give information on consumers` importance. Table *Failure Type* is designed according to the theoretical source of system component failure and available SCADA signals to the dispatching center. Table *Power Line Consumers* makes it possible to easily select the power line under the failure and simultaneously transfer the number of consumers on whole or part of the power line. If the failure is located and isolated at the end of the power line, it is possible to restore the voltage on the part of the power line in order to reduce the number of transferred consumers.

Table *Failure Component* makes it possible to gain basic information about the component quality: weak or reliable, useful to apply during network enhancement by designing the system with reliable components. Also, during maintenance activities, attention could be pay to weak component replacment in future period.

The next step of availability calculation is to feed the database with failure data, enabling the user to process the data. The most common case is to monitor and write in all acquired data during normal and accident network operation. After several years of experience of gathering data at distribution utility, it has been concluded that the database is significantly acceptable for further meaningful use and that the distribution network operation monitoring has to be permanently incorporated in everyday company activities.

3.3. Time series

Non-voltage period can be interpreted as a time series with several parts: preparation time for maintenance team to assemble and arrive, failure location time for exact failure component locating, repairing time, failure duration time for radial power lines and non-voltage time for redundant urban power lines. Preparation time is duration between failure occurence and starting moment of failure location when the maintenance-repair team is at power line area. Failure location time starts with termination of preparation time and ends with beginning of repair time. Here - as the starting and changeable value, fault location time is the difference between *Duration failure field* and *Duration prepare field* which is the overall duration for all transient faults needing no repair, where electricity supply is restored after switching on the line (feeder). For other faults above-mentioned, the difference is decreased by input variable of field *Duration repair*.

If the fault on the feeder is in the urban area with possibility of electricity feeding from some other transformer substation or feeder, the sum of location time and preparation time is equal to the duration of non-voltage time - repair starts when all the consumers are satisfied. So, feeder faults in urban areas do not have the same duration in fields *Duration failure* and *Duration non-voltage*; the first one is greater then the second. Repair time is the base point to compare effectiveness of several maintenance teams respecting the fault types and weather conditions.

The average failure location time in an urban area is almost half of the value in rural areas where feeders are usually overhead and radial. Further, the mean preparation time in urban areas is about one third of the same variable in rural areas due to several reasons. A maintenance team can easier locate the failure by feeder sections topology change in city areas, which is impossible on radial feeders in rural areas where great lengths of feeders have to be examined on foot. Moreover, feeders in urban areas are situated in the center of consume where maintenance centers are also usually situated. On the other hand, feeders in rural areas are a greater distance to the maintenance center, so the maintenance team needs extra time to arrive at fault location.

As opposed to this, the mean repair time in urban areas is four or five times greater than for radial areas where the fault has to be repaired immediately to satisfy load demand. Underground cable long repairing time is caused by the possibility of customer supply through other lines. The total sum of non-voltage duration in urban areas is about five times smaller than for rural areas.

3.4. The code

The visual Basic Code is designed as a helpful tool; it serves as a connection between the component's operational database and real power system state with fault variables enabling easier and faster data input and co-relation. During the input data process, a variety of calculations are accessible. Also, a number of useful lists such as fault causes, faulted component and fault type in the power system from data tables designed in the database are offered. After the main variables are entered, the code calculates the total fault duration, preparation duration, failure location duration and repair duration (depending on organization and staff education) and also the energy that has not been supplied. It is possible to get a number of different reports depending on chosen monitoring period in data base query. Statistic reports give duration of monitored period, total up-time and total down-time (T_{down}), number of failures, mean time to failure (*MTTF*) and mean time to repair (*MTTR*), failure intensity, failure frequency and *ASAI*.

The energy report calculates total unsupplied energy (*ENS*), average unsupplied energy per failure (*ENSF*), average unsupplied energy per year (*ENSY*), cumulative product of unsupplied consumer's number and duration of non-voltage period (C_{um}) and average of cumulative product (AvC_{um}). The last two introduced variables here are very significant and important in the decidsion process when selecting the feeder for reconstruction or planning a system development.

The period report results in basic and derived period variables are: average annual values and mean values per interruption. The following periods are: reaction, location, fault and repair periods.

It is easy to compare the same feeder indices of different periods in the past, thus enabling maintenance planning analysis of activities in the previous period and possible decisions on any corrections in the maintenance policy.

As an indication of the results, the comparison of feeders fault during two consecutive years A and B for 10 kV radial underground feeder named *Ljudevita Posavskog*, marked as 0403 further on, is given in Table 1 and Table 2.

Data presented in Table 1 indicate that there was increasing profitability for line 0403. The main cause is probably in different weather conditions that resulted in dissimilar number of faults and duration of down-time. Anyhow, the maintenance activities were improved during the year B due to decreased value of *MTTR* (Table 1) and time period of reaction (Table 2).

All the other measured faults periods are better in year A. If there is a possibility to feed feeder from another transformer substation, repair time period (Table 2) can last longer without any negative influence on availability.

Table 1. Fault indices during years A and B for 10 kV feeder 0403

Tablica 1. Pokazatelji kvarova tijekom godina A i B za 10 kV vodno polje 0403

Year	A	B
T_{down}, min	1839	2023
MTTR, h	2,043	1,983
MTTF, h	581,956	513,310
StAv	0,9965011	0,9961511
Fail. Intensity rate	5,967E-3	6,765E-3
Fail. Frequency	15	17
ENS, MWh	26,4118	31,5588
ENSF, MWh/fault	1,7608	1,8564
AvC_{um}, min/fault	2780,607	3242,102

Table 2. Fault duration periods during years A and B for 10 kV feeder 0403

Tablica 2. Vremena trajanja kvara za godine A i B za 10 kV vodno polje 0403

Year	A	B
$T_{reaction}$, min	507,00	420,00
$T_{location}$, min	623,00	1047,00
T_{fault}, min	839,00	2023,00
T_{repair}, min	484,00	7401,00
$AvT_{reaction/fault}$, min/fault	33,80	24,70
$AvT_{location/fault}$, min/fault	41,53	61,59
$AvT_{fault/fault}$, min/fault	122,60	119,00
$AvT_{repair/fault}$, min/fault	32,27	435,35

It is obvious that underground feeders have a significantly smaller number of interruptions with shorter duration. Buried feeders are most often built in the town area with another feed point. Quality of electric power supply depends mainly on reaction and location duration period.

On the other hand, radial overhead feeders outside urban areas usually do not have another power feed point and at the same time there are more smaller transformer substations 10/0,4 kV and lines are longer, usually at greater distance from maintenance and control center. Therefore, power supply quality depends directly on repair duration period. This is indicated by comparison of the computational results of a typical urban cable feeder 0407 with a typical rural overhead feeder 0801.

Table 3. Comparison of fault indices for 10 kV urban cable 0407 and rural overhead 0801 feeder

Tablica 3. Usporedba pokazatelja kvara za 10 kV vodna polja, kabel 0407 u gradu i zračni 0801 na selu

Power Line (feeder)	0407	0801
T_{down}, min	2610	7367
MTTR , h	1,673	3,721
MTTF, h	783,865	615,188
StAv	0,9978702	0,9939883
Fail. Intensity rate	11,720E-3	10,694E-3
Fail. Frequency	11	14
ENS, MWh	21,2858	9,1493
ENSF, MWh/fault	0,8187	0,2773
AvC_{um}, min/fault	1896,0	1103,9

Table 4. Comparison of fault duration periods for 10 kV urban cable 0407 and rural overhead 0801 feeder

Tablica 4. Usporedba vremena trajanja kvara za 10 kV vodna polja, kabel 0407 u gradu i zračni 0801 na selu

Power Line (feeder)	0407	0801
$T_{reaction}$, min	286,0	2501,0
$T_{location}$, min	1125,0	3326,0
T_{fault}, min	2610,0	7367,0
T_{repair}, min	2754,0	1611,0
$AvT_{reaction/fault}$, min/fault	11,00	75,78
$AvT_{location/fault}$, min/fault	43,27	100,79
$AvT_{fault/fault}$, min/fault	100,39	223,24
$AvT_{repair/fault}$, min/fault	105,92	48,82

As presented, the faults database could serve as a source of benchmark data used for any additional analysis of their drawbacks. This tool is very powerful in weakness detection or in further development system planning and prevention strategies.

Also, several statistical availability calculations of interruptions for the whole distribution power subsystem (or only for particular part or defined feeders) could be achieved, such as: number of failures, *SAIFI* (System Average Interruption Availability Index), *SAIDI* (System Average Interruption Duration Index), *ASAI* (Average Service Availability Index), *AENS* (Average Energy Not Supplied Index), *ENS* (Energy Not Supplied), *ENSY* (average value of energy not supplied per year) and *ENSF* (average value of energy not supplied per failure). All calculated availability indices for the whole system are presented in Table 5.

Table 5. System availability indices during 2,5 years

Tablica 5. Pokazatelji raspoloživosti sustava tijekom 2,5 godine

Number of faults	401
SAIFI	838,6
SAIDI, h	666,38
ASAI	0,997044
AENS, MWh/customer	1,470765
ENS, MWh	548,478
ENSY, MWh/year	235,246
ENSF, MWh/fault	1,36777

4. Case study: 35 kV distribution system *Elektra* Slavonski Brod

4.1. Substations and feeders topology

The analyzed distribution system in the area of the city Slavonski Brod covers 1983 square kilometers and population of 186000, with about 40000 consumers and peak load of 33,13 MW. The 35 kV voltage level of the case study distribution power system is presented in Figure 2.

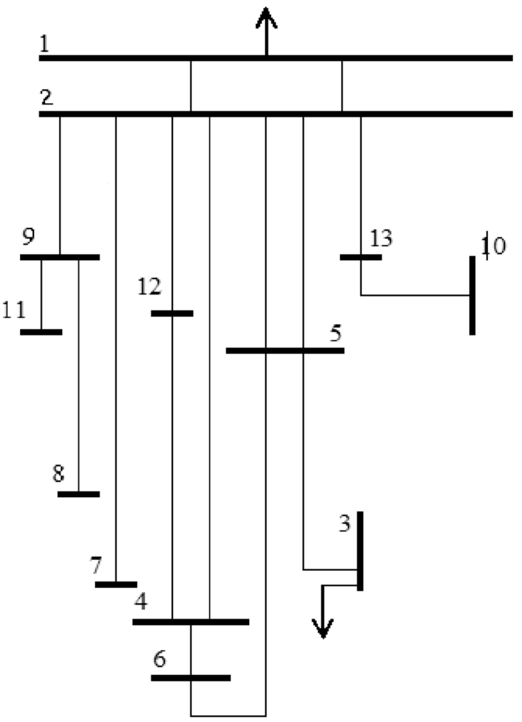

Figure 2. Case study: distribution system topology 35 kV

Slika 2. Topologija 35 kV analiziranog distributivnog sustava

The electric power network is presented by a combination of branches (feeders and transformers) and buses (nodes) in actual topological order. The nodes are points of load feed (generators and load input from a higher voltage network), points with load demand by consumers, branching points (at least one input branch and two or more output branches) and points of the feeder type changeability.

There are two following feeding HV transformer substations in the distribution network in the analyzed area: Podvinje 110/35 kV (80 MW) – basic systems feed point and Bjelis 110/35/10 kV (40 MW). Secondary systems feed point and eight transformer substations 35/10 kV; 66,7 km overhead feeders and 10,6 km buried feeders Here, branches are marked by two incident buses. Basic node and branches info are presented in Table 6 and 7 respectively.

Table 6. Case study distribution system nodes info

Tablica 6. Podaci o čvorovima analiziranog distribucijskog sustava

Node/Bus number	Bus name (location)	Transformers installed, MVA
1	Podvinje110	80,00
2	Podvinje35	80,00
3	Bjelis35	40,00
4	Slavonski Brod1	32,00
5	Slavonski Brod2	16,00
6	Slavonski Brod3	16,00
7	Brodsko Brdo	8,00
8	Oriovac	6,50
9	Brodski Stupnik	0,00
10	Donji Andrijevci	12,00
11	Bebrina	6,50
12	INA-plin	0,00
13	Topolje	0,00
14	Zrinski Frankopan	0,00

4.2. The power load flow model

The real measured load diagram during the year (Figure 3) for the power system is approximated by the stepwise levels presenting load duration curve (Figure 4). The decreasing line (Figure 3) presents actual power load duration curve for all days during the year.

The power load was adapted in form of several stepwise levels (up to 7 levels) to use the available program package COMREL for reliability evaluation of the power system with state enumeration method. Each level is marked by the system peak load level (absolute and relative to peak load of the first level) and its probability of occurrence (Table 8). The power systems load duration diagram is specified by 5 levels, where for example, the first level with the peak load (33,13 MW) has duration of 0,55 % of the time (48,18 h /year).

Table 7. Case study distribution system branches info

Tablica 7. Podaci o granama analiziranog distribucijskog sustava

Branch number	Start node	End node	Power line (feeder)/ transformer type
1	1	2	Transformer 110/35 kV, 40 MVA
2	1	2	Transformer 110/35 kV, 40 MVA
3	2	4	NA2XS(F)2Y 3(1×240) mm^2
4	2	12	Overhead line Copper 3×70 mm^2
5	2	5	Overhead line Al-steel 3×150 mm^2
6	2	5	Overhead line Al-steel 3×120 mm^2
7	5	6	IPZO 13 - 3×150 mm^2
8	4	6	IPZO 13 - 3×150 mm^2
9	3	5	Overhead line Al-steel 3×120 mm^2
10	13	10	Overhead line Al-steel 3×120 mm^2
11	2	9	Overhead line Al-steel 3×120 mm^2
12	9	11	Overhead line Al-steel 3×120 mm^2
13	2	7	Overhead line Al-steel 3×120 mm^2
14	12	14	NA2XS(F)2Y 3×(1×240) mm^2
15	14	4	IPZO 13A -3× 240 mm^2
16	2	13	Overhead line Al-steel 3×95 mm^2
17	9	8	Overhead line Al-steel 3×120 mm^2

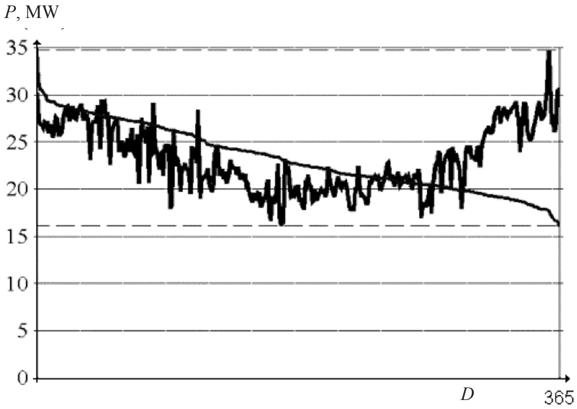

Figure 3. Electric power load diagram (oscillating) during the year (B) and the corresponding load duration curve in Area Slavonski Brod

Slika 3. Oscilirajući dijagram tereta konzuma električne energije tijekom godine B i pripadajuća godišnja krivulja trajanja opterećenja u području Elektre Slavonski Brod

Figure 4. The stepwise linear lines load characteristic during the year B in area Slav. Brod

Slika 4. Stepeničasta linearna karakteristika tereta za godinu B u području Elektre Slav. Brod

Table 8. Stepwise linear lines load duration during year B, distribution power system Slavonski Brod

Tablica 8. Stepeničasta linearna karakteristika tereta za godinu B u distribucijskom sustavu Slavonski Brod

Level	*L,* MW	Days per year, D_d	*L*/*L*peak	*T*, %
1	33,13	2	1,00	0,55
2	28,26	45	0,85	12,33
3	24,39	155	0,74	42,46
4	20,32	154	0,61	42,19
5	16,89	9	0,51	2,47

4.3. Reliability output results

After reliability calculations are performed by the program package, it is possible to compare the reliability indices of n-1, n-2 and n-3 of the branches failure level of coincidence for the case study system.

During the monitored interval, only distribution power network operating states of the same level of the coincidence level can be compared. It is obvious that n-2 reliability evaluation (one or two failures inside of the system) includes all events of n-1 level of contingency and all simultaneous failures of two components of the network. Although several buses have the possibilities to work in closed ring topology (except four transformer substations), the power system is usually used in radial topology. Table 9 indicates all radial feeders in network topology with its marks, branches and open switching devices between two buses.

As expected, that there will be significant differences in output reliability indices among different switching states of distribution network. For example, if the system operating state marked C (the best case) is compared with the one marked B (the worst operating state by the reliability aspect) a 53,94 % decrease in load curtailment probability is found, a 45,55 % decrease in expected electric energy not supplied per year, around 52,4 % decrease in load curtailment frequency and a 46,6 % decrease in load curtailment duration for case A are found. Operating states can be ranked by their expected reliability indices of n-1 coincidence as: C (as the most reliable system operating state), then D, A, E, H, G, F and finally B (as the most unreliable system operating state), as presented in table 10 for reliability calculation of n-1 level of coincidence, according to the power quality indices presented in 2.2.

Table 9. Case study distribution system operating states (radial topology)

Tablica 9. Uklopna stanja analiziranog distribucijskog sustava (radijalna topologija)

Operating states mark	Open branch 1	Open branch 2	Open branch 3
A	2-4	4-6	2-5 II
B	2-4	5-6	2-5 II
C	12-4	4-6	2-5 II
D	12-4	5-6	2-5 II
E	12-4	5-6	2-5 I
F	2-4	5-6	2-5 I
G	2-4	4-6	2-5 I
H	12-4	4-6	2-5 I

Table 10. Reliability indices of n-1 level of coincidence, case study distribution system

Tablica 10. Pokazatelji pouzdanosti n-1 reda koincidencije, analizirani distribucijski sustav

State	A	B	C	D	E	F	G	H
S	3	5	1	2	2	5	4	3
I	7	6	8	7	8	6	7	7
P	4,191	7,561	4,038	4,091	7,355	7,561	7,508	7,409
F	24,74	50,01	23,81	24,76	48,15	50,01	49,07	49,09
D	36,71	66,24	35,37	35,83	64,43	66,23	65,77	64,90
BP	3,510	6,519	3,298	3,381	6,067	6,519	6,279	6,151
ENS	20,89	34,56	18,82	19,01	30,76	34,55	32,83	30,97

Table 11. Reliability indices of n-2 level of coincidence, case study distribution system

Tablica 11. Pokazatelji pouzdanosti n-2 reda koincidencije, analizirani distribucijski sustav

State	A	B	C	D	E	F	G	H
S	37	47	23	38	29	48	41	42
I	59	52	66	52	64	52	58	50
P	4,228	7,606	4,073	4,128	7,399	7,605	7,553	7,452
F	25,15	50,48	24,21	25,18	48,61	50,50	49,54	49,56
D	37,04	66,63	35,68	36,16	64,81	66,63	66,16	65,28
BP	3,550	6,568	3,335	3,420	6,112	6,569	6,326	6,196
ENS	21,01	34,72	18,93	19,13	30,90	34,71	32,98	31,11

As can be observed in Table 11, system reliability indices of n-2 level of coincidence exibit exactly the same rank order of operating states as in the case of the reliability evaluation of the first level of coincidence.

Table 12. Reliability indices of n-3 level of coincidence, case study distribution system

Tablica 12. Pokazatelji pouzdanosti n-3 reda koincidencije, analizirani distribucijski sustav

State	A	B	C	D	E	F	G	H
S	209	236	155	248	167	237	220	258
I	237	216	273	184	273	216	237	184
P	7,553	7,606	7,398	7,453	7,399	7,606	7,553	7,452
F	49,53	50,49	48,60	49,57	48,62	50,50	49,54	49,56
D	66,16	66,63	64,81	65,28	64,81	66,63	66,16	65,28
BP	6,326	6,568	6,112	6,196	6,112	6,569	6,326	6,196
ENS	32,99	34,72	30,91	31,10	30,90	34,71	32,98	31,11

After n-3 level of coincidence reliability calculation is presented in Table 12, no significant differences in output reliability indices among different operating states could be observed. For example, if the system operating states marked C (the best case) and marked F (the worst case) are compared, only a 2,74 % decrease in load curtailment probability is found, around 11 % decrease in expected energy unsupplied per year, around a 3,76 % decrease in load curtailment frequency and a 2,73 % decrease in load curtailment duration for the best case are found.

Operating states can be ranked by their reliability indices of n-3 level of coincidence as following: C, E, H, D, A, G, B and finally F which differs compared to rankings for n-1 and n-2 level of coincidence reliability evaluation. It could be used when one or more branches are on a planned revision or maintenance for a long period of time.

5. Conclusion

The main idea of the research was to improve the fault data collection in order to enable easier identification of weak components, to recognize the most common cause of fault and to enable a more detailed availability and cost-benefit analysis in the distribution networks.

Distribution network engineers have to be informed in advance on further possible steps in operating and maintenance policy with as much savings as possible. It is far too late to perform the reliability analysis when failure occurs; it has to be done earlier by defining and directing sequence of switching devices manipulation in any circumstances. The usual way to meet these requirements is to create manipulation tables based on reliability indices of different system topologies covering all possible states in the network. Special attention has to be paid to identify the buses with critical reliability indices and of great importance in the network (whether by power demand, number of consumers or by essential location). Branches connected to these buses should be considered by optimization process for replacement, reconstruction and/or adding a parallel branch. Distribution network engineers should monitor and control the state of the system and its constituted components and to replace the weakest components either during the predictive maintenance activities or even more often after the failure occurs. The main target is to detect the weakest link in the chain and to substitute it before components break down.

When performing the availability analysis using collected data, the idea is to reduce the number of faults and interruption duration, to diminish the number and duration of non-voltage states (scheduled maintenance activities on selected branches) and to improve efficiency of repair teams during failures. Also, the most cammon causes of fault have to be eliminated if possible. After the data processing and bus index evaluation, attention has to be paid mostly on weak components or on important influential variables which give important information about the components deviation from usual reliability or quality borders and components lifetime.

The described new approach and developed application allow the user to get useful data at any time resulting in great practical improvement in power system activities, especially in reliability analysis. Distinctions of failure causes, system component or selection of duration period make it possible to perform systematic data collection and valuable quantitative reports. Several examples of useful application are: recognition of certain components with serial fault (ceramic insulators 10 kV), improvement in response time of several maintenance teams with the worst call-back results, location optimization for surge arrestors in the system and conduction of system reconstructive design plans.

It is easy to derive filtered desired data by database queries, e.g. data on only one feeder fault which the user would like to filter from all power system line faults or/and to take into account only faults in desirable duration period between two dates of user choice. It is possible to do further failure filtration by selecting only failures with same cause, failures of the same components, failures with desired duration span and so on.

Furthermore, an analysis should be performed on the cost of improving the system reliability with respect to benefits in decreasing the customer outage cost as a result of improvement, which is very important in emerging electricity market conditions and a future step in the research.

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