AN APPROACH TO MAINTENANCE OF ELECTRICAL POWER EQUIPMENT, BASED ON INDICES OF QUALITY OF SUPPLY AND FAULT CAUSE ANALYSIS

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INTRODUCTION

Elektrovojvodina is a company for distribution of electrical energy, whose basic assignment is to supply the customers with the energy of the highest possible quality.
To achieve this, indices of quality of supply must be monitored in an expert way. These indices are divided in two groups. The first group is represented by indices of quality or continuity of supply, of which the following are most often used worldwide: ENS, SAIFI, SAIDI and CAIDI. These indices are being monitored continuously in Elektrovojvodina five years in a row, from year 2002. The second group consists of indices of quality of delivered electrical energy, and those are the basic voltage characteristics : rms value, frequency, symmetry and waveform at the customer's location.
With goal to achieve all mentioned indices in accordance with requests of standards, organized expert activities must be conducted. With this in mind, Elektrovojvodina analyzes the causes of perturbation of indices of quality of supply. From the beginning of year 2002. [1] causes of customer supply interruptions are being analyzed, and particularly in detail the causes of destructive faults on HV equipment.
Based on this analysis, modern diagnostic devices were purchased, for all equipment that has the lowest level of reliability. By measuring and testing of equipment characteristics, low reliability devices are identified, and selective maintenance of exactly these elements is planned. Greater reliability of electricity distribution system is achieved this way, with minimization of maintenance expenses.

1. INDICES OF QUALITY OF SUPPLY

1.1. Undelivered electrical energy because of customer outage

When assessing the quality of supply, the most important indicator is the outage. Depending on customer's characteristics, the outage can cause larger or smaller damage, but the consequences are always unpleasant for the customer. ENS (Energy Non Supplied) shows the total undelivered electrical energy to the customer during the particular year.
For accurate analysis of influence of network elements and of outage causes, a review of indices is given, separately for power transformer and summed for power transformer and MV network. For the last four years (2002-2005) the presentation of ENS indicator for Elektrovojvodina looks as follows:

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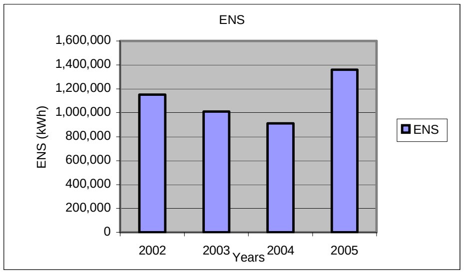
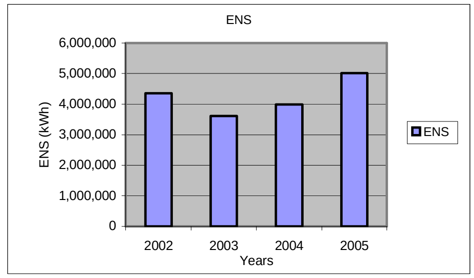
Table I - ENS

Year	2002	2003	2004	2005
ENS PT (kWh)	1.150.457	1.011.195	910.197	1.360.083
ENS PT+MV(kWh)	4.354.252	3.609.393	3.984.618	5.010.884



Sl.1. ENS for PT 110/x i PT 35/x kV



Sl.2. ENS for PT 110/x, PT 35/x and MV network

During the examined period the tendency of reducing the undielivered energy has stopped in year 2005., moreover a serious increasment has been recorded.

1.2. Average interruption frequency per active customer

The indicator that most convincingly shows the number of situations in which customers are left without supply is SAIFI (System Average Interruption Frequency Index). This indicator shows how many times, on average, has each connected customer been left without electrical energy, caused by outage of transformers only, or summed transformers and MV network. For period between years 2002. and 2005. the presentation of SAIFI indicator for Elektrovojvodina looks as follows:

Table II - SAIFI

Year	2002	2003	2004	2005
SAIFI PT (out/cust)	2,371	1,784	1,848	2,143
SAIFI PT+MV(out/cust)	5,34	4,72	5,189	6,139

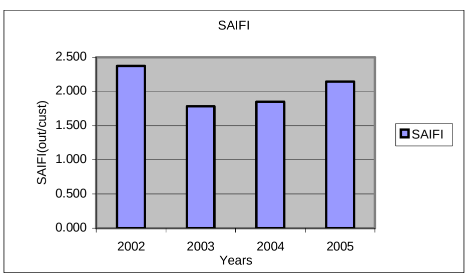


Fig.3. SAIFI for PT 110/x and 35/x kV

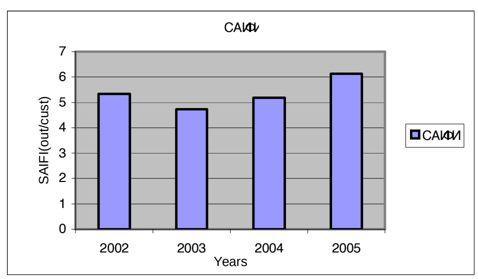


Fig.4. SAIFI for PT 110/x, PT 35/x and MV network

The examined period did not show a tendency of lowering of SAIFI indicator.

1.3. Average interruption duration per active customer

The indicator that is the best for presentation of total time during which the customers are left without electrical energy, is SAIDI (System Average Interruption Duration Index).This indicator shows for how long, on average, has each customer been left without electrical energy, caused by outage of the transformer alone, and by transformers and MV network together. For the period between years 2002. and 2005. the presentation of SAIDI indicator for Elektrovojvodina looks as follows:

Table III - SAIDI

Year	2002	2003	2004	2005
SAIDI PT (min/cust)	77,07	64,81	56,88	82,73
SAIDI PT+MV(min/cust)	234,58	219,04	232,71	298,39

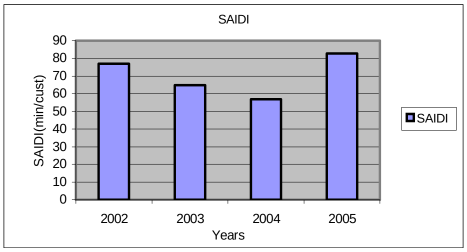


Fig.5. SAIDI for PT 110/x and 35/x kV

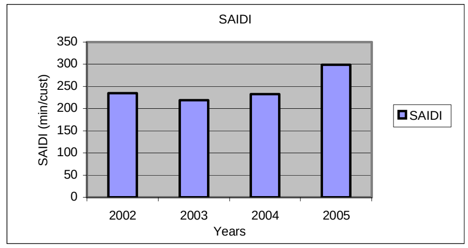


Fig.6. SAIDI for PT 110/x, PT 35/x and MV network

The examined period did not show a tendency of lowering of SAIDI indicator.

1.4. Average interruption duration for the customer under outage

The indicator that shows the time that is needed for an average customer, that was left without electrical energy to be supplied again, is CAIDI (Customer Average Interruption Duration Index). A tendency of variation of this indicator is shown for transformer outages only, and summed for transformers and MV network. For the period between years 2002. and 2005. the presentation of CAIDI indicator for Elektrovojvodina looks as foolows:

Table IV - CAIDI

Year	2002	2003	2004	2005
CAIDI PT (min/out)	32,5	36,32	30,78	38,60
CAIDI PT+MV(min/out)	43,87	46,37	44,84	48,60

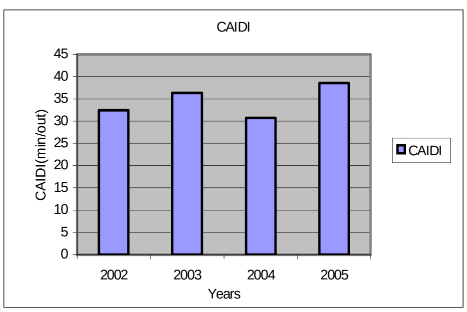


Fig.7. CAIDI for PT 110/x and 35/x kV

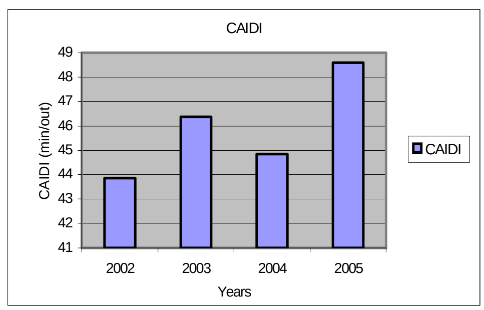


Fig.8. CAIDI for PT 110/x, PT 35/x and MV network

The examined period did not show a tendency of lowering of CAIDI indicator.

2. ANALYSIS OF MAJOR (DESTRUCTIVE) FAULTS OF POWER EQUIPMENT

Because of age, poor construction characteristics and nonexistance of adequate diagnostic devices for early phase fault detection, a lot of destructive faults happen. During these events, except for the fault of the particular equipment, secondary damage happens very often to a larger number of substation elements, situated nearby. In these cases, beside the interruption in delivery of electrical energy, substantial damages occur and fault reparation often lasts for several days. During the examined period between years 2002. and 2005. a few substation elements had particularly frequent faults.

2.1. Destructive faults on 110 kV instrument transformers

In all cases of 110kV instrument transformers destructive faults, there was a breakdown caused by electric arc, through the paper-oil insulation inside the transformer. The gases produced by arcing in oil have caused explosions, whose consequence is larger or smaller fragmentation of the lid or porcelain case. In cases of fragmentation of the porcelain case, nearby equipment was damaged by the flying porcelain fragments.

Table V - Destructive faults on instrument transformers

n.	Date of fault	IT type	Year of production	Cause	Damage costs (dinars)	SS
1	21.07.2003.	APU-123	1975	breakdown	350.000	Sombor 2
2	20.09.2003.	APU-123	1975	breakdown	350.000	Odžaci
3	24.08.2004.	4APU-123	1980	breakdown	350.000	Novi Sad 2
4	06.04.2005.	VPU-110	1964	breakdown	3.500.000	Kikinda 1
5	31.07.2005.	APU-123	1975	breakdown	4.180.000	Pančevo 3
6	26.01.2006.	VPU-123	1986	breakdown	350.000	Kovin

2.2 Destructive faults on 110 kV surge arresters

Surge arresters of the old-fashioned design, with silicon-carbide inserts and sparkers, do not have needed insulation characteristics, because of the presence of humidity in the porcelain case. This causes internal breakdown, forming the electric arc and fragmentation of porcelain case. In some cases the explosions had such destructive power, that serious damage was inflicted to the nearby equipment.

In two cases surge arresters with ZnO (zinc-oxide) inserts have fragmented. In both cases the design was old-fashioned, with porcelain case and air gaps around ZnO inserts. Insulation of the internal space, in this design is achieved by providing an under-pressure within that space. In both cases it is assumed that internal and external pressure have equaled, and that humidity has penetrated the arrester's casing. The arresters have not exploded, however their fragmentation has caused the release of the metal lid on the rope, which was enough to cause great damage to the nearby equipment. These experiences have directed to a conclusion that in the future only arresters with ZnO inserts cast in a polimer case should be purchased.

Table VI - Destructive faults on surge arresters

n.	Date of fault	SA type	Year of production	Cause	Damage costs (dinars)	SS
1	20.07.2002.	VOP 6e	1985	breakdown	120.000	Vršac 2
2	15.06.2003.	VOP 6e	1979	breakdown	120.000	S.Mitrov. 3
3	08.08.2003.	VOP 6e	1979	breakdown	120.000	S.Mitrov. 3
4	24.10.2003.	VOP 6e	1977	breakdown	2.075.000	Kula
5	10.02.2004.	VOP	1978	breakdown	570.000	S.Mitrov. 1
6	25.02.2004.	3EP2-108/86	2004	breakdown	1.550.000	Novi Sad 4
7	25.06.2004.	VOP 6e	1978	breakdown	2.450.000	Novi Sad 5
8	04.08.2005.	VOP 6e	1990	breakdown	120.000	Bajmok
9	06.09.2005.	3EP2-108/86	2003	breakdown	120.000	Novi Sad 4

2.3. Destructive faults on 110 kV bushings

Bushings did not cause a lot of destructive faults, but their breakdowns in all cases, happened inside the transformer tank, so the damages were enormous. Particular attention was drawn by breakdowns of two relativelly new bushings, of the same type and age.

Table VII - Destructive faults on bushings

n.	Date of fault	B type	Year of production	Cause	Damage costs (dinars)	SS
1	09.10.2002.	Kvp 123/630r	1974	breakdown	500.000	Pančevo 3
2	10.08.2004.	PNO 123/800	1999	breakdown	1.000.000	S.Mitrov. 3
3	01.12.2005.	PNO 123/800	1999	breakdown	4.314.000	N.Pazova

2.4. Internal faults of the 110/x and 35/x kV power transformers

Faults inside transformers lead to insulation breakdown inside the tank, and though they are not frequent, they are important because of the severe consequences. These faults leave a large number of customers without supply for a longer period of time, and the value of damage is great. These damages are often repaired in the factory or in the workshop.

Table VIII - Destructive faults on PT

n.	Date of fault	PT type	Year of production	Cause	Damage costs (dinars)	SS
1	14.09.2002.	35/10; 8	1972	breakdown	no data	NS Centar
2	21.11.2002.	110/35; 31,5	1968	breakdown	3.000.000	Novi Sad 2
3	14.03.2003.	35/10; 4	1957	breakdown	not for use	PA Pristan.
4	21.07.2003.	35/10; 4	1960	breakdown	200.000	SM Šid
5	08.10.2005.	35/10; 4	1960	breakdown	200.000	NS. Petrov

3. ANALYSIS OF NETWORK PARTS OUTAGE CAUSES

Systematic, long-term monitoring and analysis of supply interruption causes, have discovered the equipment with the lowest reliability, which should be placed in focus of maintenance planning. Theoretical analysis could finally be substituted by real, optimized maintenance, which along with minimization of expenses enables increasing of distribution system operation reliability.

3.1. Causes of 110/x kV power transformer outages

Table IX - Causes of 110/x kV PT outages

n.	Cause of outage	2002	2003	2004	2005
1	Breaker 20 kV-unreliable operation	25,5 %	20 %	14 %	20 %
2	Cause unknown	19,5 %	20 %	18 %	20 %
3	Protection 20 kV- unreliable operation	9 %	13 %	14 %	18,4 %
4	Animal	3 %	2 %	5,6 %	7,5 %
5	Fault inside power transformer	1,3 %	0 %	0,7 %	0,6 %
6	Other causes	41,7 %	45 %	47,7 %	33,5 %

3.2. Causes of 35/x kV power transformer outages

Table X - Causes of 35/x kV PT outages

n.	Cause of outage	2002	2003	2004	2005
1	Cause unknown	34 %	29 %	19 %	29 %
2	No 20 and 35 kV fider protection	10 %	29 %	22 %	13 %
3	Protection 10 kV-unreliable operation	6 %	5 %	16 %	11,5 %
4	Animal	0,8 %	1 %	3 %	4 %
5	Fault inside power transformer	0,8 %	1 %	2 %	1,5 %
6	Other causes	48,4 %	35 %	38 %	41 %

3.3. Causes of 10, 20, 35 kV MV line outages

Table XI - Causes of MV network outages

n.	Cause of outage	2002	2003	2004	2005
1	Cause unknown	no data	36 %	14,5 %	22,5 %
2	Cable breakdown-fault	no data	23,5 %	18 %	17 %
3	Insulator breakdown	no data	13,5 %	18 %	23,5 %
4	Lead severed	no data	5 %	4 %	3 %
5	Animal (bird)	no data	4 %	3 %	2 %
6	Intermittent earth-fault - lead fault	no data	no data	21 %	9 %
7	Other causes	no data	16,5 %	21,5 %	23 %

4. NEW APPROACH TO MAINTENANCE

By the beginning of year 2002. Elektrovojvodina had started to analyze the indices of quality of supply. After four-year long processing, indices analysis have forced a long-term assignment of improving the quality of maintenance of substation elements. In order for the maintenance to become optimal, with aim to minimize the expenses, it was necessary to focus the attention on the substation elements with the lowest reliability. This approach to maintenance is known worldwide as RCM - Reliability Centered Maintenance.
The assumption for implementation of such an approach to maintenance is locating of elements with low reliability in operation. Systematic, long-term monitoring and analysis of supply interruption causes have discovered the equipment with the lowest reliability, which should be in the focus of maintenance planning. However, large number of equipment, which was indicated as low reliable, makes it impossible to replace or repair all of it at the same time.
This has set a new task, how to find, within the indicated equipment, those elements that have the lowest reliability, so that by choosing the order of maintenance, the maintenance expenses could be optimized. This can be achieved by implementation of modern, microprocessor-based devices for measuring and testing of the state indicators of the equipment in operation. This way, unreliable elements are located and their faults are discovered in early phases, so that maintenance plan could include the necessary work on reparation or replacement of these elements.
With goal to realize this approach to maintenance, Elektrovojvodina has, during year 2005. and 2006., initiated purchase of state-of-the-art diagnostic devices for testing of protection equipment, power and instrument transformers, breakers, surge arresters, as well as devices for fault recording and determination of quality of delivered electrical energy.
All these activities must be supported by universal computer software [7].

4.1. Middle voltage breaker maintenance

Middle voltage 10, 20, 35 kV breakers, according to data about the supply interruption causes, have a high degree of operation unreliability. The age of the large number of MV breakers in 110/x and 35/x kV substations, brings a lot of problems to their maintenance. Defficiency of spare parts as well as devices for circuit breaker state testing, and insufficient worker training, are often causes stated as excuses for low-quality maintenance and unreliable operation of these circuit breakers. Similary, only slightly better is the situation for 110 kV breakers.
All breakers in operation can not be replaced during a longer period of time. Therefore, it is very important to approach the maintenance in accordance with RCM programe (Reliability Centered Maintenance). This approach considers application of modern circuit breaker testing devices, which can point to the critical, endangered parts of the breaker. Usage of these devices enables examination of each circuit breaker in operation, so that its main parts are tested, driving mechanism, trip coil, close coil, trip latch, close latch, DC battery, main contacts, auxilliary contacts and wiring. Very important procedure is checking of the "first trip", which determines characteristics of the breaker after a long period of inactivity [6]. Examination of each breaker leads to discovery of unreliable breakers and helps locating the causes of their improper operation. Breakers located that way, are submitted to servicing in-field or in the workshop. This way the maintenance is directed to critical elements and with minimal investments, circuit breaker reliability is increased.
Elektrovojvodina has planned to purchase a device for circuit breaker testing, in order to improve the way of maintenance and to bring operation reliability of the circuit breaker to a satisfying level.

4.2. Maintenance of 110 kV instrument transformers

According to data about outage causes and destructive faults, significant number of the faults with large damage have been caused by unreliable 110 kV instrument transformers. All faulty transformers were older than 20 years. There are more than 1000 such devices in operation, so their short-term replacing is not possible. RCM approach to maintenance requires control of the state of all instrument transformers in operation, in order to find the unreliable ones.
This can be achieved only by usage of modern equipment for measuring of insulation resistance, dielectric loss angle $tg\delta$, insulation system capacity C, and by equipment for partial discharge control by ultrasound methods and DGA (Dissolved Gas Analysis) [3,4].
Elektrovojvodina has purchased, at the end of year 2005. devices for measuring of dielectric loss angle, insulation capacity and insulation resistance. A portable device for DGA has also been

purchased, and it detects H_2, CO_2, CO, C_2H_4, C_2H_6, CH_4, C_2H_2 i H_2O, in oil samples taken from instrument transformers in operation. The devices are in use from the begining of year 2006. and they have proven their important role in maintenance - already 58 unreliable instrument transformers have been located, and their replacement is planned during the year 2006.

4.3. Maintenance of 110/x kV transformers

Most frequent faults on 110/x and 35/x kV power transformers, that lead to customer supply outages, happen because of unreliable 110 kV bushings, faults in tap changers and weak spots in the winding insulation system.
In order to discover transformer fault causes in an early phase, specialized teams must be equiped with devices for measuring of tgδ and C of the bushings, as well as of the insulation system between the windings. There is also a necessity for devices for tap changer control by measuring of contact resistances and dynamics of contact closing and opening. Possible existance of partial discharges inside the insulation, causes generation of combustible gases, which are monitored by DGA devices. For all these tests, by the end of the year 2005., expert teams of Elektrovojvodina have been equiped with the most modern equipment. By application of these devices, all 110/x kV transformers in operation will be checked during the year 2006.

4.4. Surge arrester maintenance

Analysis of 110 kV surge arrester destructive faults has implied that most of these devices with old design, with silicon-carbide (SiC) inserts and sparkers were insufficiently reliable. They can not be subjected to a reliable diagnostics, and it is concluded that they should be replaced as soon as possible. Elektrovojvodina has already replaced more than 100 of these surge arresters.
What is particularly interesting, is that from destructive fault analysis it can be seen that the faults are also possible on zinc-oxide (ZnO) surge arresters, which have an old design. Modern devices which measure the leakage current and therefore indicate the unreliable devices in operation, can also be used for their examination [5].
Elektrovojvodina has purchased one such device at the end of the year 2005., and it will be used for surge arrester testing during the year 2006.

4.5. Battery maintenance

Lead-acid batteries are the best example how RCM approach to maintenance is executed in practice. After a few destructive faults on 110/x kV substations, more than 10 years ago (year 1993.), maintenance of lead-acid batteries, as sources of 110 V DC current, was approached in a modern way. Elektrovojvodina uses a modern device for measuring of capacity, internal resistance and voltage of each separate cell as well as of the whole battery, and a device for measuring the electrolyte density in each cell. Based on this, unreliable cells are detected in an early phase, and are replaced accordingly. This has lowered the maintenance expenses, and reliability of operation has risen to such a level, that lead acid batteries are not mentioned any more as causes of customer supply outages.

4.6. Relay protection maintenance

From analysis of outage causes it can be seen that unreliable operation of protection devices has high participation in supply outages. In order to increase quality of relay protection maintenance, Elektrovojvodina has purchased a modern device for testing of protection devices on HV substations [2]. Technical characteristics have been defined for devices for testing of MV protection equipment, and they will be purchased during year 2006.

4.7. Maintenance of 10, 20 and 35 kV MV lines

Analysis of outages, due to faults in MV network, shows that 20 kV overhead lines and cable lines are equally unreliable. Most frequent causes of outages on overhead lines are: insulator breakdown, stormy weather with rain and thunder and birds as causes of earth-faults. On MV cable lines, most

frequent outage causes are: insulation breakdown or cable termination breakdown as well as cable tearing due to lack of attention during interventions of other utilities. Aiming to reduce the number of outages, systematic replacement of insulators, leads and cables is planned.
In order to reduce the outage duration in MV network, installation of a system for remote monitoring and control is planned. As a first step in this direction, two pilot systems are already installed [8].

4.8. Control of connection points overheating in substations

Connection points overheating control is also a good example of RCM approach to maintenance. More than 10 years Elektrovojvodina uses a modern infrared camera, which is used for systematic control of connection points overheating in HV substations. As a result of this work, overheating of substation elements has virtually been eliminated as a cause of customer supply outage.

4.9. Discovering of unknown outage causes

Analysis of customer outage causes shows, that too often the cause of outage in 110/x and 35/x kV substations can not be discovered. Old substations do not have remote monitoring and control systems installed, and they have protection devices which do not record electrical quantities during fault occurrence. Therefore, it is often impossible to find the outage cause. This must be enabled, in order to find the components that cause the outages to pursue with maintenance in accordance with RCM.
This is why Elektrovojvodina plans, to purchase a larger quantity of devices for recording of characteristic values, during the fault occurrence.

5. CONCLUSION

Theoretical explanation of new approach to maintenance, starts from current maintenance practice and results obtained by analysis of quality of supply indices. Analysis of fault causes identifies low-reliable substation elements. Usage of devices for state diagnosis of equipment in operation, locates unreliable elements, so the maintenance can be focused on them. RCM approach to maintenance has gained ground for full practical usage.
Set goals consist of increasing electrical equipment reliability and increasing quality of supply, and this way maintenance costs are also lowered.
Achieved results are not apparent at the beginning of activity, and systematic approach is requested as well as long-term orientation towards usage of new approach to maintenance.
Event recording in distribution network, processing of indices, planning and recording of undertaken activities, can be done efficiently only with support of computer software designed particularly for this purpose, because of large quantity of data.

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