Strategic Maintenance of 400-kV Switching Substations

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***Abstract*—This paper describes a new approach for the maintenance of high-voltage devices in switching substations that is based upon upgraded reliability-centered maintenance (RCM). In addition to periodical maintenance, the Slovenian Transmission System Operator ELES also uses an application that enables RCM. The strategic maintenance concept was developed on the basis of ongoing monitoring maintenance. It takes into consideration not only the well-known indices regarding technical conditions and importance, but also the indices for risk and environment. This new approach is demonstrated using the example of a Podlog 400-kV switching substation before and after its overhaul.**

***Index Terms*—Costs, environment, reliability, reliability-centered maintenance, risk, strategic maintenance, switching substation.**

I. INTRODUCTION

ELECTRICITY transmission companies are putting a lot of effort into prolonging the lifetimes of existing substations, in a professionally efficient manner. This can be especially ensured by maintaining an adequate level of reliability and the technical availability of high-voltage (HV) equipment. The Slovenian transmission system operator (TSO) ELES, which is legally responsible for electricity transmission system operations, and the maintenance of the transmission grid, is no exception in this respect.

ELES has to ensure that the transmission of electricity through its network is implemented efficiently, reliably, and economically. All of these requirements have to be adequately aligned with the internal rules, such as the maintenance of transmission devices [1]. This is a dynamic internal document that was prepared on the basis of scheduled times for maintenance, and the recommendations of HV equipment manufacturers. This document is frequently updated in regard to newly installed equipment and new approaches to maintenance.

The approaches to maintenance are changing as modernized manufacturing technology provides new HV switching substation elements. Even state-owned transmission companies that used to advocate preventive maintenance have started implementing reliability-centered maintenance (RCM)-based approaches. Paper [2] describes monitoring of maintenance, the conditions of the devices, and the failures of HV equipment within a switching substation using RCM within the Finnish TSO Fingrid. Another paper [3] describes the introduction of RCM methodology implementation within ELES, using the Calpos Main program package. As upgrades of RCM methodology, there are some theoretical works by various authors. The authors in [4] deal with a strategy for maintaining a transmissiongrid by taking into account profit and loss, and consequently developed a generic algorithm (GA) based on a reliability model. In [5], the authors proposed a comparison between the impacts of various maintenance strategies on the basis of reliability and cost. Paper [6] described a novel approach for the optimization of a transmission system's elements when selecting a system for maintenance planning, on the basis of long-term risk due to failures. The authors of [7] dealt with the maintenance of overhead lines using laser monitoring.

Conventional maintenance in ELES is performed in accordance with the internal rules [1] and is monitored by means of the Maximo information system (IS), which monitors the conditions of devices regarding the temporal and cost aspects. It consists of a database containing the technical data of the transmission system's elements, work orders, and work plans relating to devices, as prescribed by the internal rules [1]. The Maximo IS can also be connected to other information systems.

This paper presents a new approach for maintenance called "strategic maintenance," which is based on upgrades of the current maintenance system in ELES, in connection with existing program tools, such as Calpos Main, Maximo, Neplan, and supervisory control and data acquisition (SCADA). Strategic maintenance comprises RCM methodology, optimization of the criteria, and weights of devices' technical conditions, improvement in the reliability method for calculating the HV element's importance, risk, and the environment.

Section II deals with the maintenance of transmission devices at the 400-kV voltage level. Section III describes the implementation of RCM methodology using the Calpos Main program tool, which is presently implemented in ELES. On the basis of the currently obtained experiences of RCM implementation, Section IV describes this new approach for strategic maintenance. For verification of the new method, Section V shows an example of this strategic maintenance usage in a 400-kV Podlog switching substation, before and after its overhaul.

II. GENERAL OUTLOOK OF THE 400-kV TRANSMISSION DEVICE'S CONDITION

ELES today owns and operates with 416 km of 400-kV lines, together with six switching substations [8]. Operational

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Manuscript received April 03, 2012; revised June 20, 2012, August 02, 2012, and August 20, 2012; accepted August 25, 2012. Date of publication October 12, 2012; date of current version December 19, 2012. Paper no. TPWRD-00345-2012.

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Digital Object Identifier 10.1109/TPWRD.2012.2216552

analyses have shown that the existing 400-kV transmission network is now insufficient for Slovenian needs. Over recent years, it has become a bottleneck for electricity transits between other European countries. ELES installed a 1200-MVA 400/400-kV, phase-shifting transformer that became operational in 2010, in order to cope with this problem. This device successfully controls and regulates load flows between Slovenia and Italy.

All 400-kV switching substations are maintained on the basis of the rules on maintenance for electricity transmission devices [1]. These rules prescribe how to perform inspections, tests, control measures, revisions, overhauls, and the maintenance works. All of the previously mentioned factors are permanently and temporally defined with regard to the type and role of each HV device. ELES has, for the last ten years, statistically monitored maintenance by means of the Maximo IS. The monitoring of the maintenance and operating statistics of transmission devices indicates that it is uneconomical to perform regular maintenance on HV elements as proposed by their manufacturers. Experience has shown that maintenance intervention may have a negative impact on an HV element, either regarding its lifetime or reliable operation. Newer transmission devices need less or even no active maintenance intervention. They only require inspection and revisions. It is known that some HV elements of a transmission system need different methods of maintenance.

There are several possible strategies for solving such problems regarding HV elements' maintenance. In ELES, a decision was made, based on many years of experience, to start implementing RCM in parallel with the existing conventional maintenance, on the basis of instructions contained within the internal rules.

III. MAINTENANCE USING THE CALPOS MAIN APPLICATION

The introduction of reliability-centered maintenance in ELES started by implementing the Calpos Main application. Today, this application is used in parallel with the maintenance according to the internal rules for circuit breakers (CBs), disconnectors, instrument transformers, and power transformers. The obtained results are annual (i.e., before elaborating on the maintenance plan for the next year, compared with the maintenance carried out according to the instructions contained within the internal rules. It is on the basis of this comparison that arguments are put forward about any necessary replacement of HV equipment [9].

The Calpos Main application is based upon indices of technical condition c and importance i. The workflow is shown in Fig. 1. In the c-i diagram (Fig. 1), the new axis d_{sl} is defined by an angle of 45°, because both criteria (condition and importance) are considered equally important during the decision-making process. According to (1), the distance d is the minimum distance between this new axis and the points of the device that are defined by c and i

$$d = \frac{c+i}{\sqrt{2}}\,100. \tag{1}$$

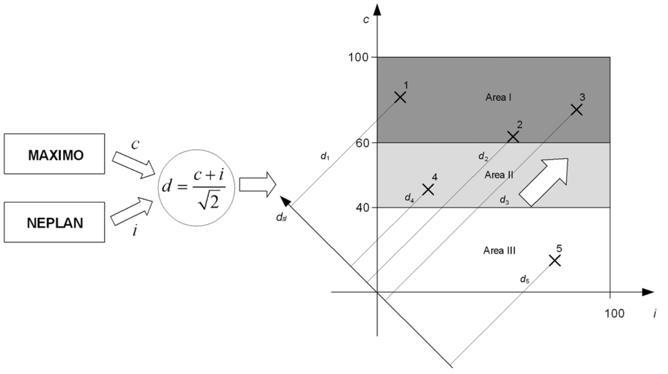

Fig. 1. Presentation of results for RCM methodology [9].

The index of the technical condition c is determined on the basis of the ELES's internal application Calpos Edit. The application Calpos Edit is connected with the database of the technical data within the Maximo IS that contains a set of criteria n with an adequate weighting factor u (from 1 to 10) and rating factor o (from 1-good to 10-bad) [9]. The value of weight u is determined according to the role and importance of the criterion n for the type of device that is installed within the transmission system. The rating factor o is determined by the engineer responsible for monitoring the switching substation for each corresponding criterion of the HV device. The general criteria are the following: time of operation stated in years ($u = 4, o = 2$ (for 20 years of operation)), operating experience over the same period ($u = 3, o = 1$ (good)), the number of operations ($u = 5, o = 6$ (high number of operations)), the type of operational mechanism, etc.

Equation (2) shows the algorithm that is used to calculate the value of the technical condition index c [10]

$$c = \frac{\sum_{\text{j}=1}^{\text{n}} (u_{\text{j}}\, o_{\text{j}})}{\sum_{\text{j}=1}^{\text{n}} u_{\text{j}}\, o_{\max}} 100 \tag{2}$$

where $o_{\max}$ equals 10, j is the counter of the criteria, and n the number of criteria. An overview of the technical conditions of each HV element within the switching substation is obtained using this algorithm. The lower the number c, the better the technical condition.

The index of importance i is calculated using the Neplan program tool. Neplan enables the analyses, optimization, management, modeling, and simulation of various operating states within the transmission network. The modular concept of this program tool makes specific settings possible with regard to those functions performed by the development and operation planners of the transmission network. The Slovenian TSO has a complete model of the national HV network in Neplan, which contains all elements (i.e., production, transmission, and load). The state with the highest annual production and load is determined by monitoring the operation of the electrical power network. These data are used in Neplan to compute adequate load flows using the extended Newton–Raphson method. It is also necessary to statistically evaluate the expected probability of outages (unavailability) during each year (h/yr) for each HV device due to scheduled maintenance and unexpected failures. The unavailability is directly connected with reliability. The Neplan program tool computes expected electricity loss W (MWh/yr) on the basis of (3) using these statistical data [10]:

$$W = f\, t\, P \tag{3}$$

where

f expected frequency of outages in one year (1/yr);

t expected average duration of an outage (h);

P active power on an HV device (MW).

The expected frequencies of outages and the duration of an outage are directly connected with the reliability of the substation's equipment.

The index of importance i is calculated using (4). The HV device with the highest value of expected electricity loss is allocated to the evaluated 100 [10]

$$i = \frac{W}{W_{\max}} 100 \tag{4}$$

where

$W_{\max}$ highest expected electricity loss (MWh/yr).

On the basis of the calculated values for i (4) and the obtained data of c (2), it is possible to plot the graph shown in Fig. 1. Fig. 1 is divided into three groups [9]:

- Area I: replacement of an HV device;
- Area II: maintenance;
- Area III: inspections defined by the instructions [1].

With regard to the values of indices c, I, and d (Fig. 1), the transmission company can decide whether to replace, maintain, or examine the device. Example: the HV device is in good technical condition ($c = 1$), the HV device is in bad technical condition ($c = 100$). The HV device is unimportant ($i = 1$) and the HV device is of great importance to ($i = 100$).

On the basis of experience obtained within the field of maintenance, ELES proposes any strategic maintenance using the Calpos Main application, as an upgrade of the current maintenance system.

IV. STRATEGIC MAINTENANCE

Over recent years, the need for introducing additional alternatives within the maintenance field has arisen for many important reasons:

- requests of the owner to optimize and reduce costs;
- modernization of the Slovenian industry needing a higher quality of electricity supply;
- Slovenia is, due to its geographical position, in demand for electricity transits;
- constant need for adapting to tough economic conditions.

For these reasons, ELES must annually monitor the conditions of devices and, if necessary, correct their plan of activities by comparing it with the conventional maintenance method according to the existing internal rules [1]. Support during the implementation of such maintenance is provided by the Maximo IS. Parallel implementation of RCM methodology is enabled by Calpos Main, together with the necessary information systems. The interest of ELES is to develop a new approach for maintenance, the so-called "strategic maintenance," in parallel with the existing conventional maintenance. The concept of strategic maintenance actually began being implemented with the introduction of Maximo IS and Calpos Main applications. Indices condition c and importance i have already been included within Calpos Main (Section III), but for strategic maintenance, some new experiences have been added to these two indices, as described in subsections A and B (Section IV). The indices presented in subsections C and D represent the new elements of strategic maintenance.

A. Technical Condition

To date, the gained experiences within the field of determining the index of technical condition c, have shown that the set of criteria is too rigid. ELES's engineers have summarized and modified the criteria and weights (described in Section III) of the Calpos Main application. The Slovenian transmission system contains the HV devices of various manufacturers. During the periods of their operation and maintenance, these devices have displayed both good and bad qualities. Year-long experiences have shown that the primary technical features of the new HV devices, like the contacts of CBs and disconnectors, reduction of losses, and electromagnetic fields and noise, have been constantly improving. Unfortunately, insufficient work has been done in the field of secondary technical features regarding HV devices, like sealing, drives, cooling, heating quality of materials, etc., which have negative impacts on the characteristics of such devices. For a smooth operation, it is important that the device has as low unavailability due to failures as possible. Therefore, the tendency is to obtain those new rearranged criteria that have so far been neglected even though they have shown a real picture of the devices' technical conditions, and to evaluate them with adequate weights. This new concept for determining index c is based on changing the structure of the criteria, using Maximo IS and SCADA, and reducing any direct human impact on the results. The remaining criteria that cannot be linked to IS will be promptly evaluated during regular annual maintenance.

B. Importance

Section III has already described how to determine the index of importance i (4). In order to elaborate any justification of major maintenance works, overhauls, or new construction, it is now necessary to update data on:

- network model at 400/220/110/35/20/10-kV voltage levels, linkable to other applications;
- production and load, obtained from SCADA;
- operational data from UTCE-DEF;
- technical characteristics of power transformers and transmission lines (reduction of reactive energy-flows);
- voltage magnitudes for each voltage level;
- probability of elements, outages (unavailability) in one year for each HV device, production sources, and load;
- maximum electricity production and load in one year; from operational experiences, the load flow on the cross-border

400-kV line Divača–Redipuglia (Italy) should be monitored since it may reach up to approximately 1800 MVA. The aforementioned data are included in the calculation of importance i and upgrade the method described in Section III. Common index d (1) strategic maintenance is not addressed.

C. Risk

Risk represents those probabilities and consequences that are connected with damage or any other negative outcome [11]. In transmission networks, there is always a risk of failure, thus causing an interruption of electricity supply. Therefore, it is in the best interests of each TSO or transmission company to reduce these risks and prevent failures, with an adequate approach to maintenance and maintenance planning. In the past, the Slovenian TSO paid insufficient attention to these risks, especially to the risk of a customer requesting financial damages due to the interruption of his or her electricity supply.

Over the last few years, ELES has also started to consider those risks within the area of maintenance regarding HV transmission equipment. The main reasons for this are the economic factors:

- An HV device should be replaced due to any bad characteristics of its technical condition, but this is not being performed due to its lesser role within the system. What is the risk of outage regarding this device?
- An HV device should be replaced but due to time-consuming bureaucratic procedures, this is not being achieved within the predicted time. What is the risk of outage regarding this device?
- An HV device should be annually maintained but due to economic-operational reasons, the scheduled outage is not being approved. Example: it is impossible to get approval for HV devices in order to ensure safety operations within the Krško Nuclear Power Plant during the periods when the power plant is in operation. What is the risk of outage regarding the HV device that could cause much greater damage than any damage due to maintenance itself?

According to the theory of risks [11], it is well known that the index of risk for a transmission system's elements is defined on the basis of two parameters (i.e., probability of appearance and the consequences caused).

The probability originates from the number of HV device failures that had to be adequately repaired and the device put back into operation within one year. At the same time, any damages or consequences, caused by an outage, are measured according to maintenance costs expressed (in h/yr) and costs of nonsupplied electricity. The costs of nonsupplied electricity C_{ned} are obtained by the following (5):

$$C_{\mathrm{ned}} = W\, C_{\mathrm{MWh}} \tag{5}$$

where

W	electricity loss, used for determining the index of importance i (4);
C_{MWh}	price of nonsupplied electricity (expressed in EUR/MWh).

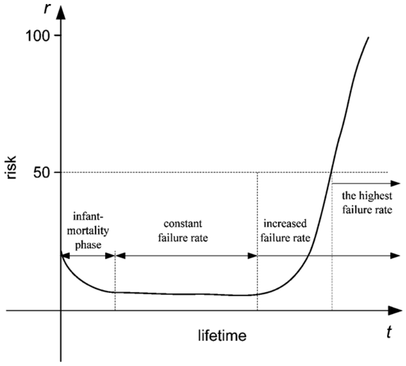

Fig. 2. Failure behavior of HV devices during their lifetime.

The financial loss from nonsupplied electricity C_{MWh} was derived at the value of the Gross Domestic Product (GDP) for Slovenia in 2011, and the number of hours without electricity supply during that year.

It is essential for a transmission company to be capable of determining the types and risks on the basis of its capabilities (experiences of maintenance personnel, type of maintenance, management of costs, etc.). The procedures and criteria of risk management are defined by the ISO 31000 standard [11].

The index of risk r in the case of strategic maintenance includes the cost of scheduled maintenance Q_{vzd} (expressed in h/yr) and the costs of nonsupplied energy due to stochastic failures C_{ned} (5). Limits are determined by risk index r because of a common methodology for strategic maintenance. Value 1 represents low risk, while the value 100 represents high risk.

The value of risk index r that can be related to individual HV elements or to the entire HV bay is written as

$$r = \frac{1}{2}\left(\left|1 - \frac{Q_{\mathrm{vzd}}}{Q_{\mathrm{vzd}_{\max}}}\right| + \frac{C_{\mathrm{ned}}}{C_{\mathrm{ned}_{\max}}}\right) 100 \tag{6}$$

where

Q_{vzd}	actual cost of maintenance (expressed in h/yr), obtained by Maximo IS;
Q_{vzdmax}	predicted cost of maintenance (expressed in h/yr), that have to be performed according to instructions [1];
C_{ned}	real costs of nonsupplied electricity due to a stochastic failure;
C_{nedmax}	maximum possible costs of nonsupplied electricity due to a stochastic failure with the usage of the maximum power P.

When displaying the risk index r, a chart can be used relating to the lifetime of the observed HV element t (Fig. 2).

The curve in Fig. 2 has a bathtub shape and shows the expected frequencies of outages regarding HV devices through their lifetimes. At the beginning of its lifetime, an HV device is in the so-called infant-mortality phase, which does not last long. Then, it is in a constant failure rate. After a certain operational lifetime of a device, that device is in the area of increased risk that rapidly increases over time. At one moment, the risk is greater than 50 and reaches the highest failure rate [6].

D. Environment

Insulation and cooling media are often involved during the maintenance of HV devices. These media are the transformer and hydraulic oils, SF_6 insulation gas, nitrogen, and various dissolvers and lubricants that, with their chemical properties, represent a potential danger to the environment. Media that are in liquid aggregation states can physically manage more easily, for example: oil-pit, leakage of oil instrument transformers and CBs. A bigger problem is represented by media that are in gaseous aggregation states, such as sulfur hexafluoride, SF_6.

In HV CBs, SF_6 gas is, in most cases, used as an arc extinguishing and insulation medium. SF_6 is a very stable and inert gas, colorless, nonpoisonous, inflammable, and insoluble in water. SF_6 is, due to its chemical properties, very usable in HV elements although it is classified as a greenhouse gas. Excessive greenhouse gas emissions cause increases in global temperatures [12]. SF_6 has absorption characteristics within a range of 7 and 13 μm, and relatively a 23 900 times higher global warming potential (GWP) than CO_2 [12], [13].

ELES is, as a holder of the environmental certificate ISO 14001, obliged to identify environmental impacts and to reduce them. In the case of SF_6, it is obliged to monitor emissions into the air and reduce them. The EU has adopted a series of environmental regulations that include the treatment of SF_6 gas. The most important is the regulation on certain fluorinated greenhouse gases. The Republic of Slovenia has harmonized national codes using this regulation.

The environmental index e addresses the leakages of SF_6 gas in CBs. Some CBs that have been in operation for several years are causing uncontrolled emissions of SF_6 into the atmosphere. The reasons mainly are in the material (the aging, sealing, corrosion, and dilatation of flanges) and rapid changes in temperature (and, consequently, the contraction and expansion of gas within chambers). On the basis of the aforementioned reasons, the environmental index e is calculated using the following:

$$e = \left(\frac{m_{\mathrm{iz}}}{m_{\mathrm{SUM}}} f_{\mathrm{t}}\right) 100, \tag{7}$$

where

f_{t}	allowable factor of annual leakage;
m_{iz}	mass of uncontrolled emissions in the atmosphere (in kilograms);
m_{SUM}	total mass of gas in the circuit breakers (in kilograms).

The environmental index e consists of the quantity of gas and leakage factor. The quantity of gas in the CB is presented by the ratio between the mass (kg) of uncontrolled emissions in the atmosphere and the total mass (kg) of gas in the CB. A leakage factor f_{t} has to be included in (7) in order to adapt the environmental index e to other indices,. The allowable factor for leakages originates from the past experiences of IEC 62271-303:2008 standards, where an annual level of leakage is prescribed [12]. Table I shows the allowable leakage factor f_{t} that prescribes allowable quantities of gas leakage m_{IEC} with regard to the manufacturing year of a CB.

TABLE I
ALLOWABLE LEAKAGE FACTORS OF SF_6 FOR 400-kV HV BAYS

Year	f_{t}	m_{IEC} [%]
before 1986	10	10
between 1986 and 2006	100	1
after 2006	500	0.5

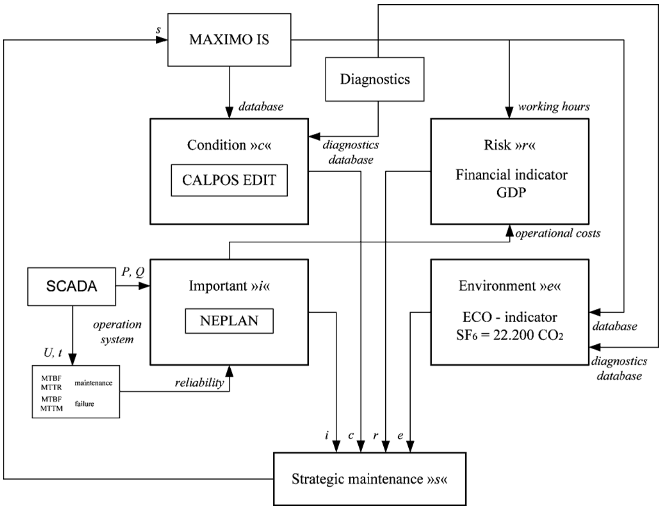

Fig. 3. Block diagram of strategic maintenance methodology.

E. Index of Strategic Maintenance

Following discussion of all the indices, it is possible to introduce the index of strategic maintenance s, as defined

$$s = \frac{(c+r)(i+e)}{c+r+i+e}. \tag{8}$$

Equation (8) presents mathematical derivation where all indices are equally considered.

Strategic maintenance represents the total index s that is defined by the indices of the technical condition c (2), importance i (4), risk r (6), and environmental e (7). The values for the strategic maintenance indices are normalized using values from 1 (good) to 100 (bad).

In practice, it turns out that the values for the strategic maintenance index can be very different. For this reason, the following three areas were created according to the values of index s

- $0 < s \leq 40$: monitoring conditions of HV devices (Area III);
- $40 < s \leq 70$: maintenance of HV devices (Area II);
- $70 < s \leq 100$: replacement of HV devices (Area I).

Fig. 3 shows a block diagram of strategic maintenance methodology.

The Maximo IS contains a database of basic technical data on HV devices in switching substations. Maximo IS, through work orders, keeps a record of working hours and, thus, the costs of HV devices' maintenance. In order to calculate the index of technical condition c, the application Calpos Edit obtains a list of data from Maximo IS, while diagnostic assessment is obtained from the switching substation operators. The Neplan application obtains the operational data (active and reactive powers of generation and load) needed to compute the index of importance i from the SCADA system. SCADA also returns

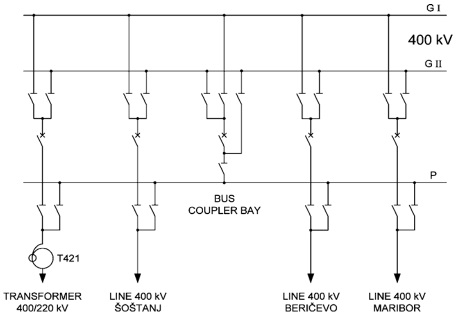

Fig. 4. One-line diagram of the 400-kV switching substation.

TABLE II
INDEX OF RISK FOR 400-kV HV BAYS IN THE PODLOG SUBSTATION BEFORE OVERHAUL

HV bay	Q_{vzd} [h]	Q_{vzdmax} [h]	C_{ned} [k€/y]	C_{nedmax} [k€/y]	r
line Beričevo	40	32	39.9	48	54
line Šoštanj	32	32	14.8	15.3	48
line Maribor	40	32	31	48	45
transformer T421	36	32	13.9	14.4	55
bus coupler	32	32	14.9	18	42

TABLE III
RESULTS OF THE COMPUTATION FOR INDICES OF STRATEGIC MAINTENANCE FOR 400-kV HV BAYS BEFORE THE OVERHAUL

HV bay	*c*	*i*	*r*	*e*	*s*
line Beričevo	80	93	54	78	75
line Šoštanj	71	66	48	64	62
line Maribor	71	74	45	100	70
transformer T421	79	54	55	73	65
bus coupler	82	93	42	100	75

data on the unavailability of HV devices due to stochastic failures and scheduled maintenance, which are obtained from operational data (voltage against the interruption duration). In order to compute the index of risk r, the operational costs are obtained by means of the Neplan application. Data on the working-hours regarding maintenance are taken from the Maximo IS. The environmental index e is calculated using data from Maximo IS (list of CBs), which contains a database of technical data regarding HV devices, and diagnostic data on the filling of CBs' chambers with SF_6. Indices c, i, r, and e are co-joined by (8) to calculate the index s, which is forwarded to Maximo IS as information for displaying and for making decisions on maintenance.

V. EXAMPLE OF STRATEGIC MAINTENANCE IN THE PODLOG 400-kV SWITCHING SUBSTATION

The 400-kV Podlog switching substation before and after its overhaul is presented in this section in order to confirm the success of this new approach for maintenance, using the example of strategic maintenance.

The Podlog substation is one of six nodes within the Slovenian 400-kV network and was constructed between 1978 and 1982. Fig. 4 shows the one-line diagram of the 400-kV switching substation. The topology of this switching substation has remained unchanged since then:

- double busbar arrangements with two main busbars (GI and GII);
- one auxiliary busbar (P);
- three line-bays (Šoštanj, Maribor, and Beričevo);
- transformer bay T421–400/220 kV, 400 MVA;
- bus coupler bay;
- two measurement and grounding bays.

In 2008 and 2009, an overhaul of this 400-kV switching substation was performed due to worn-out equipment. One of the arguments for this decision to overhaul was also the result of analysis obtained by the Calpos Main application. Below is a presentation of the analyzed results with the inclusion of strategic maintenance for the year 2007 (i.e., before the overhaul).

The technical condition of the devices that were approximately 30 years old, were the following:

CBs:

- problems with the reliabilities of the hydraulic drives;
- typical failures (insulation poles had loosened at the junctions);
- corrosion of flanges and sealing surfaces;
- increased emissions of SF_6.

Disconnectors

- cracks in the insulators;
- difficulties with heating on the contacts;
- difficulties with the driving mechanisms.

Instrument transformers

- condition of the material;
- oil leakages;
- occurrences of explosive gases in the oil.

The power transformer T421 400/220 kV, 400 MVA, had never been overhauled; therefore, it was untreated during the analysis. The index of technical conditions c (Section IV-A) of the HV bays as was obtained by using the Calpos Edit application, is shown in Table III. For the sake of easier understanding due to the extensive amount of data, the results from the computation regarding technical conditions and their importance, are shown in aggregated form for individual 400-kV HV bays.

The index of importance i (Section IV-B), as obtained from the Neplan application, showed that the importance of some disconnectors was seen as lower than the importance of CBs due to different busbar arrangements. Existing practice has shown that an overhaul should be carried out for the entire HV switching substation bay; therefore, the highest value for all HV elements was taken for indices i and c, as shown in Table III.

The index of risk r (Section IV-C) was computed using (6). The actual working hours on maintenance Q_{vzd} were taken from Maximo IS, while the actual costs of nonsupplied electricity C_{ned} caused by a stochastic failure were computed for each individual HV bay using the Neplan application. The results from the computations regarding the situation before the overhaul in 2007 are shown in Table II for each of the individual 400-kV HV bays of the Podlog substation.

It is evident from Table II that the individual HV bays had different values for risk index r. Those were mostly caused by the maximum electrical power P, the values regarding the unavailabilities of HV bays during a year due to stochastic failures, and

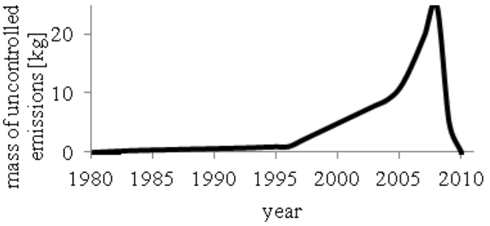

Fig. 5. Uncontrolled emissions of SF_6 from 400-kV CBs.

the working hours spent on maintenance Q_{vzd}. The price of non-supplied electricity C_{ned} amounted to 3000 EUR/MWh. The instructions for maintenance [1] and from the manufacturers require that 400-kV HV devices that are older than 15 years need more maintenance as well as preventive inspections and repairs than newer devices. In the presented case, the predicted time of maintenance $Q_{\mathrm{vzd}_{\max}}$ before the overhaul amounted to 32 h.

From the environmental point of view (Section IV-D), the results are as follows: Before the overhaul of the 400-kV switching substations, the share regarding uncontrolled emissions of gases into the atmosphere m_{iz}, which is included in (7), had started to grow. The graph in Fig. 5 shows the use of SF_6 for the maintenance of adequate pressure in the chambers of all 400-kV CBs within the Podlog substation. Fig. 5 shows that the consumption of SF_6 in 1995 reached 1 kg/yr. In the year 2000, it grew to 5 kg/yr. In 2008, it increased from 15 to 25 kg/yr, mostly because of leakage and a consequent failure of CBs in the bay of line to Maribor, and in the bus coupler bay (Table III, column e). In 2009, the consumption fell to 5 kg/yr due to the renewal of the aforementioned two CBs. After the overhaul, the consumption of gas stopped since the devices were new and did not leak gas.

The mass regarding any uncontrolled leakage of gas m_{iz} for each individual circuit breaker in the HV bay was used for determining environmental index e before the overhaul. The mass of all gas m_{SUM} in all three phases in the 400-kV CB amounted to 54 kg. For the allowable leakage factors in the CBs, the value of 10 was taken (Table I), since they had already been manufactured in 1978. The computed environmental index e (Table III) amounted to 100 for the bay of the line to Maribor and for the bus coupler bay, which was caused by the aforementioned failure. For the bays of lines to Beričevo and Šoštanj, it amounted to 78 and 64, respectively, while for the bay of TR T421, it amounted to 73. The result depended upon the quantities of SF_6 emitted into the atmosphere. The SF_6 leakage occurred in early Spring, which is characterized by high-temperature variations during the day that have negative impacts on any expansion of the material.

The computed indices of strategic maintenance for the 400-kV switching substation at the Podlog substation before the overhaul in 2007, as shown in Table III, may lead to the following conclusions: In regards to the methodology of strategic maintenance (Section IV.E), the bay of the line to Beričevo and the bus coupler bay belonging to Area I needed the replacement of HV devices. The other HV bays were classified to the upper part of Area II, where the HV devices needed to be maintained. With regard to the results in Table III, the methodology of strategic maintenance confirmed the eligibility of the overhaul, which was subsequently fully performed.

TABLE IV
RESULTS OF COMPUTATION FOR INDICES OF STRATEGIC MAINTENANCE FOR 400-kV HV BAYS AFTER THE OVERHAUL

HV bay	*c*	*i*	*r*	*e*	*s*
line Beričevo	5	67	28	0	22
line Šoštanj	4	39	48	0	22
line Maribor	5	51	13	0	13
transformer T421	1	31	21	0	13
bus coupler	6	67	28	0	22

Table IV shows the results for the indices of strategic maintenance for HV bays after the overhaul of the entire 400-kV switching substation.

As is evident from Table IV, the index for technical condition c for all bays amounted from 1 to 6 (good), which confirmed that the HV devices were new. The index of importance i for the bay of the line to Beričevo amounted to 67, for the bay of the line to Maribor to 51, for the bay of the line to Šoštanj to 39, for TR T421 to 31 and for the bus coupler bay to 67. The bus coupler bay was given the highest value for the index of importance i because of its role within the switching substation. The index of importance i was reduced in comparison with the situation before the overhaul (Table III). The main reason lies in the reduced load flows through the 400-kV transmission network due to the installation of 1200-MVA, 400/400-kV phase-shifting transformer at the Divača substation. The second reason was the reduced probability of HV devices' outages due to stochastic failure and maintenance. The risk r had various values due to operating conditions. There was no contribution to risk due to maintenance since the devices were maintained in accordance with the instructions [1]. The risk was higher for the line to Šoštanj and amounted to 48, which was due to constant operation throughout the year of Unit 5 at the Šoštanj thermal power plant. The second of the higher values for risk, amounting to 28, was for the line to Beričevo and the bus coupler bay. TR T421 had a risk index of 21, while for the line to Maribor, it amounted to 13. The value of environmental index e was 0 for all HV bays, which meant that the chambers in all of the installed new CBs were expectedly tight.

The total index s was within the range from 13 for the line Maribor and for TR T421 to 22 for the other line. All five HV bays (Section IV-E) belonged to Area III, where monitoring of the HV devices' conditions was required. The values for index s will increase over time until the method and strategy regarding maintenance are changed.

VI. CONCLUSION

This paper introduced a new concept for the strategic maintenance of HV elements in switching substations. This new method was verified by examples of strategic maintenance in the Podlog 400-kV switching substation. The result of analysis with the new method of strategic maintenance before the overhaul of the Podlog substation confirmed that it was necessary. The analysis using the new method of strategic maintenance after the overhaul also confirmed that the values of the strategic maintenance index were such that they belonged to Area III, which only requires the monitoring of HV devices' conditions.

The transmission system operator ELES before 2006 had performed time-periodical maintenance, which means maintenance independent from the situation in the power system. After that, an upgrade of this method began including the conditions and importance of HV devices according to the annual working plan. The benefit has been a more economical usage of maintenance finance resources. The proposed new strategic maintenance is based on simultaneously considering devices' conditions (during the monitoring) and calculations of devices' importance, environmental conditions, and risks. Evaluation results of this maintenance strategy enable a system operator to determine and replace the HV device which is the most important for system reliability. Improved benefits of such maintenance result in a reduction of maintenance costs and, at the same time, contribute to system reliability which affects utility, system operators, and users.

For the final implementation of this method, it will be necessary to optimize the criteria of technical conditions and to upgrade the index of importance with the inclusion of a modified reliability method that also considers reactive energy. The decisive factor for the success of implementing this new method of strategic maintenance in ELES will be the mutual automatic connection of all of the aforementioned information systems, such as Maximo, SCADA, Neplan, and Calpos Edit. Practical usage of strategic maintenance instead of the current maintenance according to instructions can be introduced gradually into ELES.

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