Prioritization procedure for transmission network assets revitalization

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Abstract - **Important issue for Transmission System Operators is how to deal with older transmission assets. To ensure system reliability and security over long time frame, Transmission System Operators have to develop appropriate methodology and procedure for transmission assets/facilities revitalization or replacements. This paper describes one possible way to prioritize transmission facilities for revitalization. Example of this procedure is also given in the paper.**

Keywords: **System reliability and security, Transmission assets, Revitalization, Replacements, Transmission network development.**

1. INTRODUCTION

Transmission assets ageing process has significant impact on system operation and planning. Unreliable and older facilities may jeopardize overall system reliability and security, while increasing transmission system operational costs. Important issue for Transmission System Operators is to choose an optimal moment for assets revitalization or replacement, in order to ensure satisfactory level of system reliability and security. At the same time, revitalization or replacement costs should be reduced and economically justified.

Transmission facilities and equipment (overhead lines, cables, transformer stations, protection devices, measuring, telecommunication devices etc.) are getting older during their operation. Each transmission facility and equipment has its expected lifetime. Transmission facilities are expected to operate under declared characteristics during their lifetime, without significant number of failures or problems. For the same group of transmission facilities, lifetime may vary under quite wide range because different influential factors like climate, operational or constructional ones. During aging process equipment slowly losses its characteristics so number and duration of failures increase. With satisfactory and periodical maintenance activities transmission facilities may operate reliable under declared characteristic, until this is not possible any more due to their obsoleteness.

Transmission facilities and equipment were revitalized or replaced in the past mostly because their characteristics didn't match technical operational requests any more due to constant load increase. Today, in the age of slower load increase and competitiveness in the electricity business, revitalization activities are mostly initiated by technical (system reliability and security) and economical requests. Transmission system operators are responsible for reliable and secure network operation in an open electricity market environment, while operating a network in an economically reasonable way at the same time. Moreover, large number of transmission equipment constructed during last century will exceed their lifetime soon.

One possible way to prioritize transmission facilities for revitalization or replacement will be described in this paper. The prioritization is based on three main criteria:

- transmission facilities real condition,
- transmission facilities importance in the system, and
- expected costs which are caused by particular transmission facilities.

Each criterion is evaluated using points (marks) from 0 to 5. Transmission facilities revitalization list includes only facilities appraised with certain number of points. The candidates for revitalization or replacement are chosen among transmission facilities when following requests are fulfilled:

- facility oldness is larger than its expected lifetime,
- facility average last five-years unavailability is larger than average five-years unavailability of the group of the same facilities (overhead lines, cables, transformers etc.),
- facility average last five-years outages number is larger than average five-years outages number of the group of the same facilities,
- facilities that not fulfill established technical criteria,
- facility book value is zero.

Transmission facility real condition is determined according to past and present performance indicators like: last five-years average forced and planned unavailability and the number of outages, maintenance record, operational conditions in the past, visual examination and laboratory tests.

Transmission facility importance evaluation is based on the probabilistic simulations of transmission system operation. Probabilistic simulations are based on Monte-Carlo method, DC power flows and linear programming. Simulations are performed for one year period taking into account different parts of annual load duration curve. Expected undelivered electricity costs and re-dispatching costs caused by particular transmission facility with different values of its unavailability are calculated.

Expected costs caused by particular transmission facility are also evaluated using probabilistic simulations. Facility unavailability is divided into four groups: 1) forced unavailability caused by internal reasons; 2) forced unavailability caused by external reasons, 3) planned unavailability caused by internal reasons; 4) planned unavailability caused by external reasons.

Predicted future unavailability is computed or estimated and simulations are repeated with the new value. Difference between annual undelivered electricity costs and re-dispatching costs with facility unavailability for year N and facility unavailability for year N+1 is the measure for point determination in this category.

Application of proposed prioritization procedure on real power system is included in the paper.

This paper is structured as follows: after introduction estimations on transmission facilities/equipment lifetimes are given in Chapter 2; observed terms and reliability indicators are explained in Chapter 3; Chapter 4 describes probabilistic method used for calculation of overhead lines, cables and transformers importance for a system; Chapter 5 defines revitalization criteria while procedure for transmission facilities revitalization prioritization is described in Chapter 6. Example of described method is given in Chapter 7. The paper concludes with Chapter 8.

2. TRANSMISSION FACILITIES/EQUIPMENT LIFETIME

The function $\lambda(t)$ of unavailability or number of failures of transmission network facilities or equipment during their lifetime has anomalous shape that can not be easily mathematically formulated. That shape is similar to the bath-tub because it is characterized with increased number of failures at the beginning of usage ($d\lambda(t)/dt<0$), small number of failures and unavailability during long time of the normal usage ($d\lambda(t)/dt\sim0$), and significantly increased number of failures after certain years when facility or equipment has reached its lifetime ($d\lambda(t)/dt>0$). It is very hard or almost impossible to predict a time moment or period when certain transmission facility or equipment reaches the point when number of failures and unavailability are significantly increased after many years of normal usage. Time moment (period) in which the period of normal usage turns into the period of obsolescence for certain transmission facilities or equipment is called expected lifetime. Estimations on expected lifetimes for different groups of transmission equipment are published in [1-3]. According to [3], following lifetimes are defined for the most important groups of transmission facilities/equipment:

- 46 to 54 years for ACSR conductors, depending on influential factors (climate, operational, constructional), with standard deviation of ±15 years,
- 63 years for steal towers, with standard deviation of ±21 years,
- 42 years for transformers, with standard deviation of ±8 years,
- 38 to 43 years for circuit breakers with standard deviation of ±6 years, depending on voltage level, type, etc.
- 39 to 42 years for other bays equipment (measure transformers, disconnections), with standard deviation of ±8 years.

3. TERMS AND RELIABILITY INDICATORS

Revitalization is a group of activities and associated investments conducted in order to prolong transmission facilities or equipment lifetimes, or more specifically the period of normal usage characterized with small number of failures and unavailability. Transmission equipment may be refurbished, replaced or upgraded through the revitalization process. Maintenance activities are separated from revitalization activities, but influential to them because periodical and comprehensive maintenance will prolong the need for revitalization.

The failure of a transmission facility (equipment, device, or component) is the occurrence when facility moves from normal to fault state. Transmission facility may be in operation or out of operation after failure occurred. Outage is the occurrence when facility moves form operational state to non-operational state due to failure. Planned outage is the occurrence when facility is moved to non-operational state intentionally, while forced outage is the occurrence when facility is moved to non-operational state due to failure, non-intentionally. Planned and forced outages may have internal or external reasons. Reasons for planned outages are maintenance activities, deformations removal, operational circumstances etc., while reasons for forced outages are short-circuits, overloading, voltage deviations etc. Planned and forced outages with internal reasons are those outages that are caused by internal failures on specific facility, while external reasons come outside the specific facility. Number of failures (λ) and average failure duration (t), observed in a one-year period, define facility or equipment unavailability (q):

$$q\ (\%) = \left(\lambda \cdot t / 8760\right) \cdot 100 \qquad (1)$$

Unavailability may be expressed as a sum of unavailability because forced outages (q_f) and planned outages (q_p), while both may be divided according to internal or external reasons (q_{fi}, q_{fe} *and* q_{pi}, q_{pe}).

$$q = q_f + q_p = q_{fi} + q_{fe} + q_{pi} + q_{pe} \qquad (2)$$

where:

q is transmission facility unavailability,

q_f is transmission facility unavailability caused by forced outages,

q_p is transmission facility unavailability caused by planned outages,

q_{fi} is transmission facility unavailability caused by forced outages with internal reasons,

q_{fe} is transmission facility unavailability caused by forced outages with external reasons,

q_{pi} is transmission facility unavailability caused by planned outages with internal reasons,

q_{pe} is transmission facility unavailability caused by planned outages with external reasons.

We may assume roughly that aging process influences unavailability caused by forced and planned outages with internal reasons, while unavailability caused by forced and planned outages with external reasons stays constant during a long period of time. If detailed and comprehensive historic statistical data about specific equipment unavailability are available, together with outages causes, short-term future unavailability of the most important transmission facilities (overhead lines, cables, transformers) may be predicted using the following approach:

- for transmission facilities younger than expected lifetime for the same group of facilities (overhead lines, cables, transformers) short-term future unavailability is calculated as average unavailability from historic statistical data,
- for transmission facilities older than expected lifetime for the same group of facilities, short-term future unavailability is calculated assuming that unavailability's caused by forced and planned outages with external reasons are constant and equal to the average values from the past, while unavailability's caused by forced and planned outages with internal reasons are defined each by normal probability function with mean and standard deviation calculated from historical data.

Mathematically this may be expressed as follows:

a) for facilities younger than expected lifetime of the same group of facilities

$$q = \frac{1}{N}\sum_{n=1}^{N} q_{fi,n} + q_{fe,n} + q_{pi,n} + q_{pe,n} \tag{3}$$

where q is a facility unavailability, N is total number of years with historic statistical data, $q_{fi,n}$, $q_{fe,n}$, $q_{pi,n}$ and $q_{pe,n}$ are unavailability caused by forced outages with internal and external reasons in the year n, and unavailability caused by planned outages with internal and external reasons in the year n, respectively.

b) for facilities older than expected lifetime of the same group of facilities

$$q = q_{fi} + q_{fe} + q_{pi} + q_{pe} \tag{4}$$

$$q_{fe} = \frac{1}{N}\sum_{n=1}^{N} q_{fe,n} \tag{5}$$

$$q_{pe} = \frac{1}{N}\sum_{n=1}^{N} q_{pe,n} \tag{6}$$

$$q_{fi}(avg) = \frac{1}{N}\sum_{n=1}^{N} q_{fi,n} \tag{7}$$

$$q_{pi}(avg) = \frac{1}{N}\sum_{n=1}^{N} q_{pi,n} \tag{8}$$

$$\sigma_{fi} = \sqrt{\frac{\sum_{n=1}^{N}(q_{fi,n} - q_{fi}(avg))^2}{(N-1)}} \tag{9}$$

$$\sigma_{pi} = \sqrt{\frac{\sum_{n=1}^{N}(q_{pi,n} - q_{pi}(avg))^2}{(N-1)}} \tag{10}$$

Using normal probability functions:

$$f(x) = \frac{1}{\sigma_{fi}\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{q_{fi} - q_{fi}(avg)}{\sigma_{fi}}\right)^2} \tag{11}$$

$$f(x) = \frac{1}{\sigma_{pi}\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{q_{pi} - q_{pi}(avg)}{\sigma_{pi}}\right)^2} \tag{12}$$

with probability that x is between x_1 and x_2 (where x is equal to q_{fi} and q_{pi} separately):

$$P(x_1 < x < x_2) = \frac{1}{\sigma\sqrt{2\pi}} \int_{x_1}^{x_2} e^{-\frac{1}{2}\left(\frac{x - \bar{x}}{\sigma}\right)^2} dx \tag{13}$$

and defining the probability of 95 %, it's possible to determine the value of x (q_{fi} and q_{pi}) using iterative approach. That value represents predicted future unavailability caused by forced and planned outages with internal reasons.

4. TRANSMISSION FACILITIES SYSTEM IMPORTANCE CALCULATIONS

In order to determine the role that each transmission facility (overhead line, cable, transformer) has in a system, probabilistic computations are performed. Probabilistic simulations are based on Monte-Carlo method, DC power flows and linear programming. For each operational state, Monte-Carlo method is used to determine operational condition of lines, transformers and generators (in or out of operation), and then DC network calculation is conducted. Generators are initially engaged according to their costs (economic dispatch). Optimization algorithm is as follows:

$$Min\sum\left(C_i\left(P_i\right) + \delta\sum\left(D_i^0 - D_i\right)\right) \tag{14}$$

where $C_i(P_i)$ are generators production costs, δ is unit electrical energy not supplied costs, D_i^0 is load in node i, and D_i is load in node i after load rejection. Optimization algorithm is subjected to constraints concerning generators power output limits, DC power flow equitation's and branches capacity limits. If DC power flow calculation shows overloading of some branch(es), optimization algorithm tries to find a new operational state by re-dispatching generators or performing load rejection. After several thousands of DC load flow calculations average operational costs are calculated, as a sum of average production costs and average loss of load costs. Simplifying annual load duration curve and performing calculations for different load levels on that curve, it is possible to estimate annual system operational costs *OC(j)* related to year *j*.

Branches (overhead lines, cables, transformers) importance for a system is then calculated as difference between system average annual operational costs for different values of branch unavailability (average, predicted, full unavailability, full availability). For each branch, following costs are calculated:

OC (j) – system operational costs in year *j*, with average branches unavailability,

$OC_k\ (j)$ – system operational costs in year *j*, with predicted unavailability of branch *k* (using method described in the previous chapter),

$OC_{k100}\ (j)$ – system operational costs in year *j*, with full unavailability of branch *k* (out of operation),

$OC_{k0}\ (j)$ – system operational costs in year *j*, with full availability of branch *k* (permanently in operation, without outages).

5. REVITALIZATION CRITERIA

The candidates for revitalization or replacement are chosen among transmission facilities when following requests are fulfilled:

- facility oldness is larger than its expected lifetime,
- facility average last five-years unavailability is larger than average five-years unavailability of the group of the same facilities (overhead lines, cables, transformers etc.),
- facility average last five-years outages number is larger than average five-years outages number of the group of the same facilities,
- facilities that not fulfill established technical criteria,
- facility book value is zero.

Revitalization criteria are divided between technical and economical criteria. Technical criteria are:

- technical incorrectness of facility or associated equipment,
- technical failure of facility or associated equipment, that are economically unjustified to be removed,
- unsatisfactory facility characteristics related to expected operational circumstances (capacity, short-circuit level etc.),
- discrepancy between characteristics and technical or environmental directives,
- inadequate human resources educated for facility (equipment) management,
- inadequacy of spare parts.

Economical criteria are:

- Positive NPV of investment related to revitalization or replacement activities,
- Large maintenance costs, commensurable with revitalization costs.

6. PRIORITIZATION PROCEDURE

The prioritization procedure for revitalization is based on three main criteria:

- transmission facilities real condition,
- transmission facilities importance in the system, and
- expected costs which are caused by particular transmission facility.

Transmission facility real condition is determined according to past and present performance indicators like: last five-year average forced and planned unavailability and the number of outages, maintenance record, operational conditions in the past, visual examination and laboratory tests. Based on the estimation and examination of real condition, each facility, revitalization candidate, is appraised with points between 0 and 5:

- 0 points for excellent condition,
- 1 point for good condition, without detected need for revitalization, with small maintenance costs,
- 2 points for satisfactory condition, without detected need for revitalization, but with moderate maintenance costs,
- 3 points for non-satisfactory condition, need for certain revitalization activities, with moderate or increased maintenance costs,
- 4 points for bad condition, need for larger revitalization activities, increased maintenance costs, and
- 5 points for technically incorrect condition or failure condition that is economically unjustifiable to remove, facility satisfies technical criteria described before.

Transmission facility importance for a system is determined according to probabilistic calculations and system operational costs defined in chapter 4. Based on the calculations, each facility, revitalization candidate, is appraised with points between 0 and 5:

- 0 points when facility doesn't have any role in a system ($OC_k\ (j) - OC\ (j) = 0$; $OC_{k100}\ (j) - OC\ (j) = 0$; $OC\ (j) - OC_{k0}\ (j) = 0$),
- 1 point when facility has very small role in a system ($OC_k\ (j) - OC\ (j) = 0$; $OC_{k100}\ (j) - OC\ (j) \neq 0 < A$; $OC\ (j) - OC_{k0}\ (j) = 0$),
- 2 points when facility has small role in a system ($OC_k\ (j) - OC\ (j) = 0$; $OC_{k100}\ (j) - OC\ (j) \neq 0 < A$; $OC\ (j) - OC_{k0}\ (j) \neq 0 < A$),
- 3 points when facility has moderate role in a system ($OC_k\ (j) - OC\ (j) \neq 0 < A$; $OC_{k100}\ (j) - OC\ (j) \neq 0 < A$; $OC\ (j) - OC_{k0}\ (j) \neq 0 < A$,),
- 4 points when facility has significant role in a system ($OC_k\ (j) - OC\ (j) \neq 0 < A$; $OC_{k100}\ (j) - OC\ (j) \neq 0 > A$; $OC\ (j) - OC_{k0}\ (j) \neq 0 > A$),
- 5 points when facility has extremely significant role in a system ($OC_k\ (j) - OC\ (j) \neq 0 > A$; $OC_{k100}\ (j) - OC\ (j) \neq 0 > A$; $OC\ (j) - OC_{k0}\ (j) \neq 0 > A$).

Variable *A* is revitalization investment/costs annuity defined as:

$$A = \frac{i \cdot I}{1 - \frac{1}{(1+i)^T}} \quad (15)$$

where I is revitalization investment/costs, i is discount rate and T is expected facility/equipment lifetime.

Expected costs which are caused by particular transmission facility are determined according to probabilistic calculations and system operational costs defined in chapter 4, based on the facilities unavailability prediction according to the method described in chapter 3. Based on the calculations, each facility, revitalization candidate, is appraised with points between 0 and 5:

- 0 points when facility doesn't cause any costs in a system between two parallel years ($OC_k\ (j+1) - OC_k\ (j) = 0$),
- 1 point when facility causes small costs in a system between two parallel years ($OC_k\ (j+1) - OC_k\ (j) > 0 < 0.01\ A$),
- 2 points when facility causes moderate costs in a system between two parallel years ($OC_k\ (j+1) - OC_k\ (j) < 0.1\ A$),
- 3 points when facility causes larger costs in a system between two parallel years ($0 < OC_k\ (j+1) - OC_k\ (j) < 0.5\ A$),
- 4 points when facility causes significant costs in a system between two parallel years ($0.5\ A < OC_k\ (j+1) - OC_k\ (j) < A$),
- 5 points when facility causes extremely significant costs in a system between two parallel years ($OC_k\ (j+1) - OC_k\ (j) > A$).

The prioritization list for short-term revitalization is determined taking into account the sum of points from all three categories. Transmission facilities, revitalization candidates, enter the list if:

- the sum of points from all categories is equal or larger than 10,
- have 5 points in at least one category.

Transmission facilities are listed according to the maximum sum of points in all categories.

7. EXAMPLE

Previously described approach was used for short-term revitalization list creation in the Croatian transmission network (figure 1) [4].

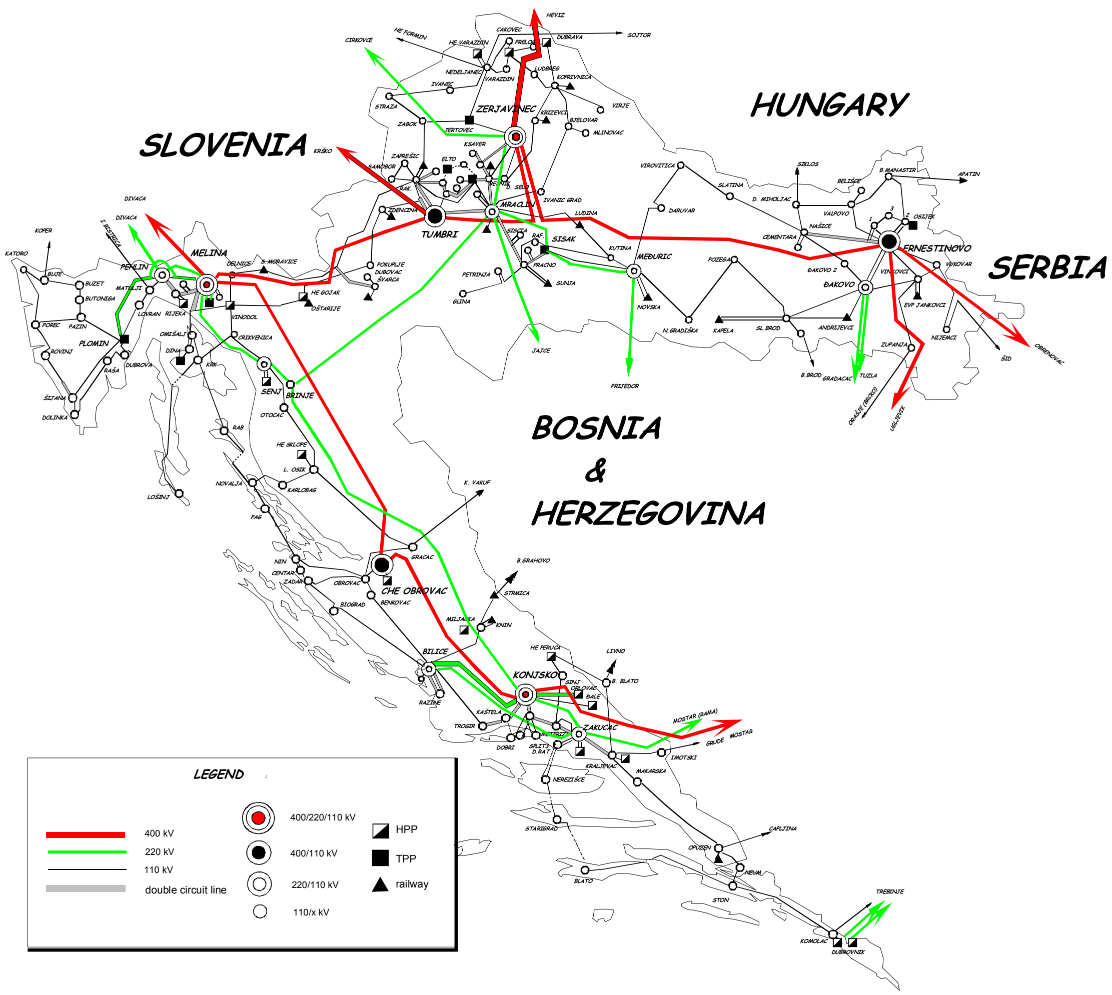

Fig. 1. Croatian transmission network (2006).

Transmission network comprises 400 kV, 220 kV and 110 kV lines, with total length of more than 7000 km, mostly build between 1950 and 1980. 38 % of overhead lines 220 kV and 110 kV have reached or exceeded expected lifetime of 45 years (figures 2 and 3). Only five transformers 220/110 kV are older than expected lifetime (42 years).

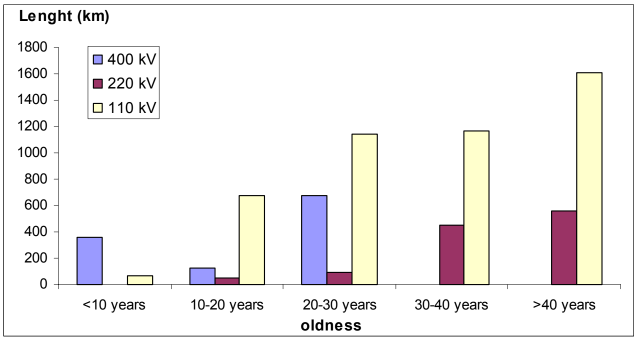

Fig. 2. Overhead lines and cables oldness in the Croatian transmission network.

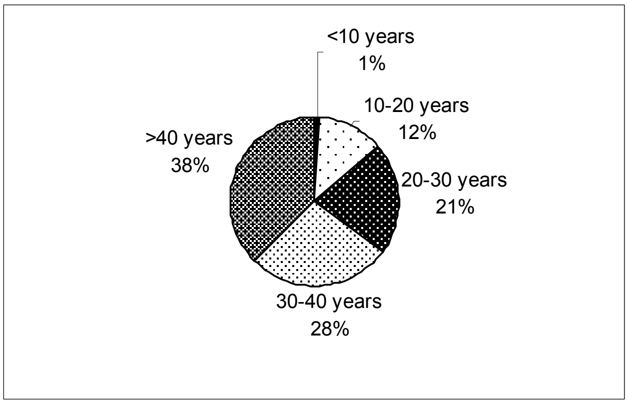

Fig. 3. The proportion of 220 kV and 110 kV overhead lines and cables according to their oldness in the Croatian transmission network.

Statistical data about unavailability, number of failures, failures causes etc., exist for time period 1995 – 2004 [5]. Statistical data show that reliability indicators are quite good although the network is old. Average lines unavailability for observed time period ranges between 1.4 % (110 kV lines) and 3.2 % (400 kV lines). Lines unavailability caused by forced outages ranges between 0.22 % (110 kV and 400 kV lines) and 0.4 % (220 kV lines). At the same time number of failures is generally increased, but obviously duration of failures is relatively short. Average transformers unavailability for observed time period ranges between 1.1 % (110/x kV) and 4.6 % (400/110 kV). Transformers unavailability caused by forced outages ranges between 0.29 % (110/x kV) and 1.87 % (400/110 kV).

Revitalization list was made observing overhead lines, cables and transformers only, not entering into detailed equipment or component analysis. Bays equipment, protection devices, measuring devices etc. were not analyzed. Nine 220 kV lines and sixty four 110 kV lines were selected as revitalization candidates, according to criteria described in chapter 5. Four transformers 220/110 kV were observed also as revitalization candidates. Based on lines and transformers real condition and probabilistic simulations for three years period (2005-2007), taking into account several scenarios dependent on the hydrological conditions and system balance, revitalization list was made that comprises 30 overhead lines, all of them in operation under 110 kV voltage level. It is expected that transmission system operator will perform his activities related not only to revitalization and replacements, but also to maintenance, according to that list.

8. CONCLUSION

Transmission assets ageing process has significant impact on system operation and planning. Having in mind the fact that modern power systems were constructed mostly after Second World War, it is obvious that many transmission facilities and associated equipment are old and maybe not reliable any more. Important issue for Transmission System Operators is to choose an optimal moment for asset revitalization or replacement, in order to ensure satisfactory level of system reliability and security.

Approach for overhead lines, cables and transformers revitalization prioritization is described in this paper. The prioritization is based on three main criteria:

1) transmission facilities real condition,
2) transmission facilities importance in the system, and
3) expected costs which are caused by particular transmission facility.

Every criterion is evaluated using points (marks) from 0 to 5. Transmission facilities revitalization list includes only facilities appraised with certain number of points. Described procedure was applied on overhead lines and transformers revitalization prioritization in the Croatian transmission network.

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