KRITERIJI I METODA ODREĐIVANJA PRIORITETA ZA REVITALIZACIJU PRIJENOSNE MREŽE

THE CRITERIA AND METHOD OF DEFINING PRIORITIES FOR THE REVITALIZATION OF THE TRANSMISSION NETWORK

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U radu se razmatra problematika starenja jedinica prijenosne mreže i utjecaja starenja na pouzdanost elektroenergetskog sustava, te su postavljeni kriteriji i metodologija za izradu liste prioriteta za revitalizaciju vodova i transformatora u prijenosnim elektroenergetskim mrežama. Kriteriji za revitalizaciju temelje se na stvarnom stanju jedinice, te ulozi i važnosti jedinice unutar elektroenergetskog sustava. Probabilističkim simulacijama rada sustava i mult-iscenarijskom analizom izračunavaju se očekivani godišnji operativni troškovi rada sustava, a na temelju razlike tih troškova pri različitim razinama neraspoloživosti promatranih jedinica kvantificiraju se pojedini kriteriji ovisni o ulozi i važnosti jedinica, te se izračunava indeks važnosti kandidata za revitalizaciju. Na temelju tog indeksa, te indeksa stanja pojedinačnih kandidata za revitalizaciju, izrađuje se jedinstvena lista prioriteta vodova i transformatora za revitalizaciju.

The work examines the problem of the aging of transmission network units and the impact of it on the reliability of the electric power system (EPS). The criteria and methodology are defined for compiling a priority list for the revitalization of lines and transformers in transmission networks. The criteria are based on the real condition of a unit and the role and relevancy of the unit within the EPS. Through a probabilistic simulation and a multi-scenario analysis the expected annual operating costs of the system are calculated. Based on the difference of these costs at different unavailability levels of the observed units, the individual criteria, which are dependent on the role and relevance of the observed unit, are quantified and the significance index of the revitalization candidates is calculated. Based on that index, and the condition index of individual revitalization candidates, a single priority list of lines and transformers for revitalization is compiled.

Ključne riječi: lista prioriteta; pouzdanost elektroenergetskog sustava; revitalizacija; starenje jedinica prijenosne mreže
Keywords: priority list; reliability of the electric power system; revitalization; the aging of transmission network units

1 UVOD

Oprema i uređaji u elektroenergetskoj mreži troše se i stare za vrijeme svoje životne dobi. Svaki dio opreme ima svoje vlastito životno vrijeme unutar kojega se očekuje da će raditi u skladu s deklariranim karakteristikama bez većeg broja zastoja i kvarova. Funkcija neraspoloživosti ili broja kvarova jedinica (elemenata, uređaja) prijenosne mreže ima nepravilan oblik i ne može se matematički izraziti. U stvarnosti ona ima oblik tzv. kade, što znači da je karakterizira povećani broj kvarova (time i neraspoloživost) u početku korištenja jedinice nakon njenog puštanja u pogon, zatim dugačko razdoblje normalnog korištenja gdje je broj kvarova mali i približno konstantan, te na kraju razdoblja korištenja naglo povećani broj kvarova koji se događaju radi starosti promatrane jedinice.

U sustavu s većim brojem starih i dotrajalih jedinica čija je neraspoloživost povećana dolazi do narušavanja pouzdanosti, time i do smanjene sigurnosti opskrbe potrošača električnom energijom, odnosno povećanih troškova rada elektroenergetskog sustava u cjelini.

U ovom radu opisana je originalna metodologija i kriteriji na temelju kojih se mogu odrediti liste prioriteta za revitalizaciju vodova i transformatora u prijenosnim elektroenergetskim mrežama, s ciljem održavanja zadovoljavajuće sigurnosti pogona čitavog elektroenergetskog sustava (EES) i smanjenja operativnih troškova rada sustava.

2 OČEKIVANA ŽIVOTNA DOB JEDINICA MREŽE

Očekivanu životnu dob pojedinih jedinica mreže nije moguće unaprijed odrediti pa se stoga određuju očekivane veličine na temelju što većeg broja uzoraka istovrsnih jedinica. Iako se približavanje životnoj dobi može relativno sigurno predvidjeti na temelju pogonskih podataka i različitih terenskih i laboratorijskih ispitivanja opreme, uglavnom se promatraju grupe istovrsnih jedinica mreže te se definiraju približne veličine očekivane životne dobi dalekovoda (električki i građevinski dijelovi), kabela, transformatora, polja, ostale opreme u transformatorskim stanicama, sustava zaštite, telekomunikacija i sustava upravljanja te drugog.

Ukoliko se promatraju kvarovi električne opreme (uređaja, jedinica mreže) mogu se razlikovati dvije osnovne vrste kvarova prema njihovom uzroku: slučajni kvarovi – uzrokovani uglavnom vanjskim uzrocima, te kvarovi zbog starosti – uzrokovani promjenom karakteristika opreme tijekom njenog dugotrajnog korištenja. Osim te dvije vrste kvarova

1 INTRODUCTION

Equipment and devices in an electric power network are deteriorating and aging during their lifetime. Each equipment part has its own lifetime within which it is expected to operate in accordance with its declared characteristics without a greater number of outages and failures. The unavailability function or the number of failures on the units (elements, devices) of the transmission network is irregularly shaped and cannot be mathematically expressed. In reality it is bathtub-shaped, meaning that it is characterized by an increased number of failures (and thereby unavailability) in the initial period of using a unit after its commissioning, followed by a long span of normal use with a small and approximately constant number of failures, and, finally, a period of rapidly increasing number of failures occurring because of the age of the observed unit.

In a system having a greater number of old and deteriorated units with a higher level of unavailability, disrupted reliability begins to prevail and thereby reduced electricity supply security resulting in an increase in the operating costs of the EPS as a whole.

This work describes an original methodology and criteria on the basis of which priority lists for the revitalization of lines and transformers in transmission networks can be defined with an aim to keep a satisfactory level of operational security of the whole EPS and to reduce its operating costs.

2 LIFE EXPECTANCY OF NETWORK UNITS

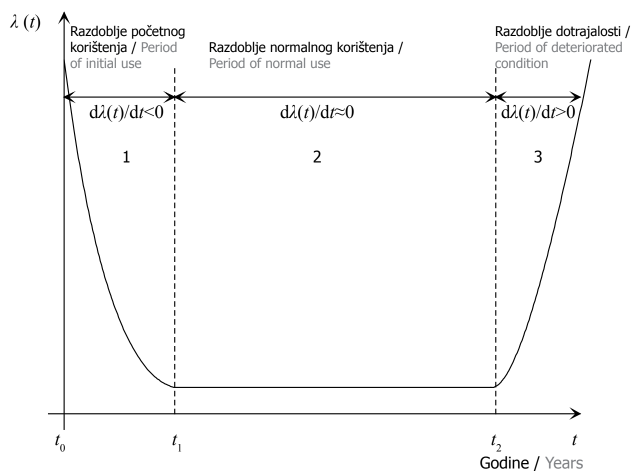
The life expectancy of individual network units cannot be defined beforehand, so expected values are defined on the basis of the greatest possible number of units of the same type. While the approaching end of the lifetime can be predicted with relative certainty, based on operation data and visual inspection and laboratory tests on conducted on equipment, mostly observed are the groups of network units of the same type so as to define the approximate life expectancy values of transmission lines (electrical and construction parts), cables, transformers, fields, other equipment in substations, protection systems, telecommunications, control systems and other.

Amongst the observed failures on electrical equipment (devices, network units) two basic types of failures by their cause can be distinguished: random failures – mostly caused by external influences and age-related failures – caused by changed equipment characteristics after a long use. In adpostoje još i kvarovi uzrokovani manjkavom izvedbom opreme koji uglavnom dolaze do izražaja u početnoj fazi korištenja opreme. Nadalje, kvarovi električne opreme mogu se podijeliti na temelju mjesta nastanka uzroka kvara na vanjske i unutarnje kvarove, te na temelju mogućnosti saniranja kvara na popravljive i nepopravljive kvarove. Starenjem opreme u mreži dolazi do povećanog broja kvarova, time i do povećanog broja ispada, zastoja i neraspoloživosti jedinica mreže. Kako se oprema približava kraju svoje očekivane životne dobi aktivnosti i financijska sredstva koje je potrebno uložiti u njeno održavanje značajno se povećavaju.

Funkcija broja kvarova, neraspoloživosti ili intenziteta kvarova za električnu opremu ima poznati oblik kade (slika 1), te je nije moguće matematički formulirati za svaki pojedinačni slučaj.

dition to these two types of failures there are failures caused by poor construction, coming to the fore largely in the initial stage of equipment use. Furthermore, failures on electrical equipment can be divided by the place of their cause into external and internal ones, and, by their reparability, into reparable and unreparable ones. With the aging of equipment there is an increasing number of defects and thereby an increasing number of outages, failures and unavailability of network units. With the approaching end of the life expectancy of equipment, the funds to be spent on its maintenance tend to rise significantly.

The function of the number of failures, the unavailability or intensity of failures on electrical equipment is bathtub-shaped (Figure 1) and cannot be mathematically formulated for each particular case.



Slika 1 — Funkcija intenziteta kvara
Figure 1 — Defect intensity function

Unutar funkcije intenziteta kvarova razlikuju se tri područja vremena korištenja električne opreme:

— područje 1 između t_0 i t_1 – predstavlja razdoblje početnog korištenja, gdje nakon puštanja u pogon opreme dolazi do nastanka određenog broja kvarova. Kvarovi su uglavnom uzrokovani konstrukcijskim i dizajnerskim pogreškama pri izradi opreme. Funkcija intenziteta kvarova je padajuća $(d\lambda(t)/dt)<0$, jer sve kvarove otklanja proizvođač opreme radi garancije koja se traži,
— područje 2 između t_0 i t_1– predstavlja razdoblje normalnog korištenja gdje je intenzitet kvarova približno stalan, a kvarovi su uglavnom uzrokovani vanjskim utjecajem i slučajnog su karaktera. Funkcija intenziteta kvarova je približno konstantna $d\lambda(t)/dt \approx 0$,

Within the failure intensity function three areas of the use of electrical equipment can be distinguished:

— area 1 between t_0 and t_1 – represents the period of initial use, where after commissioning a certain number of failures occur. These failures are largely caused by structural and design errors during equipment manufacture. The failure intensity function is descending $(d\lambda(t)/dt)<0$, because all defects are corrected under the manufacturer's warranty,
— area 2 between t_1 and t_2 – represents the period of normal use, where the failure intensity is approximately constant and failures are largely caused by external influences and are of random nature. The failure intensity function is approximately constant $d\lambda(t)/dt \approx 0$,

— područje 3 nakon točke t_2 – predstavlja razdoblje dotrajalosti, gdje intenzitet kvarova naglo raste dok ne dostigne točku kada pogon više nije moguć. Funkcija intenziteta kvarova je rastuća $\mathrm{d}\lambda(t)/\mathrm{d}t > 0$. U tom su području dominantni kvarovi uzrokovani starošću opreme i značajno nadmašuju kvarove čiji su uzroci slučajnog karaktera.

Točka t_2 na slici 3 predstavlja vrijeme normalnog korištenja pojedine električne opreme, odnosno približno se može nazvati očekivanom životnom dobi. Nakon te točke razdoblje korištenja opreme moguće je produljivati uz smanjenu pouzdanost, odnosno raspoloživost jedinica, te povećana ulaganja u održavanje i popravke. Točku u vremenu, odnosno ograničeno vremensko razdoblje kada razdoblje normalnog korištenja prelazi u razdoblje dotrajalosti razlikuje se za svaku pojedinačnu opremu u mreži, te ovisi o nizu ostalih unutarnjih i vanjskih faktora, a nemoguće ju je sa sigurnošću predvidjeti. Idealno bi bilo revitalizaciju opreme, odnosno svake pojedinačne jedinice mreže provesti u trenutku t_2 ili neposredno nakon njega, čime bi se optimizirala financijska sredstva i razdoblje korištenja jedinice mreže.

Vrijeme prelaska iz razdoblja normalnog korištenja u razdoblje dotrajalosti za svaku pojedinačnu opremu/jedinicu u mreži ovisi o više faktora, kao što su: pogonskih uvjeta (opterećenja, naponi, kratki spojevi, broj sklopnih operacija i dr.), vanjskih utjecaja (klima, okoliš, izloženost atmosferskom onečišćenju itd.), izloženosti mehaničkom stresu, te izloženosti termičkom stresu.

Postoji više indikatora da se promatrana oprema nalazi na kraju razdoblja normalnog korištenja, odnosno očekivane životne dobi, kao što su: povećana neraspoloživost, povećani broj kvarova, povećani troškovi održavanja ili kraj razdoblja korištenja istovrsne opreme u mreži. Izuzev kraja životne dobi pojedinih jedinica mreže radi starosti, trajni izlazak iz pogona i zamjena pojedinih jedinica također može biti uzrokovana drugim razlozima strateške, ekonomske ili tehničke naravi.

Procjene očekivane životne dobi električkih komponenata nadzemnih vodova u dostupnoj literaturi kreću se između 40 i 60 godina. Pri tom se pojedine komponente (izolatorski članci, dijelovi ovjesne i spojne opreme, pojedine dionice vodiča i zaštitne užadi) parcijalno zamjenjuju tijekom eksploatacije dalekovoda. U [1] definirana je prosječna vrijednost očekivane životne dobi Al/Č vodiča od 54 godine, s odstupanjem od ±14 godina, te čelično-rešetkastih stupova od 63 godine ± 21 godinu. Pravi se razlika između vodova koji se nalaze unutar normalnog okruženja, te vodova koji se nalaze unutar izrazito zagađenog područja, čija očekivana životna dob električkih komponenata

— area 3 after point t_2 – represents the period of deteriorated condition, where the failure intensity rapidly grows until reaching a point where operation is no longer possible. The failure intensity function is ascending $\mathrm{d}\lambda(t)/\mathrm{d}t > 0$. In that area the dominant failures are caused by the age of equipment and significantly exceed the failures caused by random factors.

Point t_2 in Figure 3 represents the time of normal use of an electrical equipment, and can be approximately attributed to life expectancy. After that point the period of equipment use can be prolonged with reduced reliability/availability of units and increased spending on maintenance and repair. The point in time, or the limited period of time when the period of normal use passes into the period of deteriorated condition, differs from equipment to equipment in the network, depending on a variety of other internal and external factors, and cannot be predicted with any fair amount of certainty. The revitalization of equipment or each particular network unit would be ideal to carry out in moment t_2 or immediately thereafter, whereby the finances and the period of using the network unit would be optimized.

The time of transition from the period of normal use to the period of deteriorated condition for each particular equipment/network unit depends on a number of factors, such as operation conditions (loads, voltages, short-circuits, number of switching operations, etc.), external influences (weather, environment, exposure to atmospheric pollution, etc.), exposure to mechanical stress and thermal stress.

There is a number of indications that the observed equipment has reached the end of normal use or life expectancy, such as: greater unavailability, increased number of failures, higher maintenance costs or the end of using the same type of equipment in network. Apart from the end of the lifetime of certain network units as a result of age, permanently discontinued operation and replacement of individual units can also be caused by other reasons of strategic, economic or technical nature.

The assessments of the life expectancy of the electrical components of overhead lines in accessible literature vary between 40 and 60 years. Some transmission line components (insulators, parts of suspension and couplings, some conductor sections and protective wire) are partially replaced during the exploitation of the transmission line. Literature [1] estimates the average value of an ACSR conductor at 54 years with a deviation of ±14 years, and of steel towers at 63 years ± 21 years. A distinction is made between the lines in a normal environment and those in an excessively polluted environment where the life expectancy of electrical iznosi 46 godina ± 15 godina. Prema [2] očekivana životna dob za stupove dalekovoda iznosi između 50 godina i 70 godina, a 35 godina do 50 godina za vodiče, izolaciju, te nosnu i spojnu opremu.

Prema dosadašnjim iskustvima u pogonu visokonaponskih kabela i raspoloživih tehničkih podataka očekivana životna dob za uljne kabele iznosi oko 50 godina [2]. Za određivanje povoljnog trenutka zamjene ovu vrijednost moguće je korigirati ovisno o opterećenju kabela (sadašnjem i očekivanom), zabilježenim pogonskim događajima i uvjetima u kojima je kabel položen. Očekivana životna dob ostalih vrsta procjenjuje se u suradnji s proizvođačima. Prema [1] očekivana životna dob za uljne kabele iznosi 52 godine, s odstupanjem od ±20 godina.

Na pravo stanje energetskih transformatora točnu informaciju, na temelju koje se može donijeti odluka o revitalizaciji, može dati jedino potpuna analiza pogonskih događaja, te dijagnosticiranje njihovog stanja. Zbog visokih investicijskih troškova velikih energetskih transformatora njihova je zamjena određena starošću, odnosno oni ostaju u pogonu sve dok je to tehnički moguće. Ekonomski razlozi za zamjenu poput smanjenja gubitaka unutar transformatora gotovo nikad nisu motiv za zamjenu. Veći popravci ostarjelih transformatora također se gotovo nikad ne prakticiraju budući da su troškovi popravaka visoki. Važni faktori koji utječu na karakteristike transformatora su vlaga i kisik. Povećanjem sadržaja vlage u ulju smanjuje se njegova probojna čvrstoća. Vlaga također može oštetiti čvrstu (papirnatu) izolaciju namotaja transformatora, kao i kisik i toplina [3] i [4]. Generalno se može zaključiti da na starenje transformatora glavni utjecaj imaju vlaga, toplina i kisik, najviše ovisni o pogonskim uvjetima kojima je transformator izložen u vremenu njegova korištenja. Očekivana se životna dob velikih energetskih transformatora prema dostupnim procjenama kreće između 42 godine [1] i 50 godina [5], uz pretpostavku njihovog redovitog održavanja i nepostojanja većih kvarova koji bi ga trajno oštetili.

3 PROCJENA BUDUĆE NERASPOLOŽIVOSTI JEDINICA MREŽE

3.1 Promatrane jedinice prijenosne mreže

Prijenosnu mrežu sačinjava čitav niz različitih objekata i uređaja, odnosno jedinica, komponenta i elemenata. Najvažniji su: nadzemni vodovi, kabelski vodovi, transformatorske stanice zajedno s transformatorima i poljima te ostalom opremom, zaštitni uređaji, mjerni uređaji, telekomunikacij-

components is 46 years ± 15 years. According to [2], life expectancy varies between 50 and 70 years for transmission line towers, and between 35 years and 50 years for conductors, insulators, suspension and couplings.

According to experiences gained so far in the operation of high-voltage cables and available technical data, the life expectancy of oil cables is around 50 years [2]. For assessing the favorable replacement timing, this value can be corrected in dependence on the cable load (present and expected), recorded operation events and conditions under which the cable is laid. The life expectancy of other types is assessed in conjunction with the manufacturers. According to [1], life expectancy of oil cables is 52 years with a deviation of ±20 years.

It is only a comprehensive analysis of operation events and their diagnosis that can provide accurate information about the real condition of power transformers, based on which a decision on revitalization can be made. Due to the high cost of investment in large power transformers, their replacement is determined by age, in other words, they remain in operation as long as technically possible. The economic reasons for their replacement, such as reduction of losses within the transformers, are virtually never a motivation strong enough to undertake replacement. Major repair works on old transformers are, due to high costs of such repairs, virtually never practiced either. Important factors influencing the characteristics of transformers are humidity and oxygen. Increased humidity content in oil reduces their breakdown strength. Humidity can also impair the solid (paper) insulation of transformer windings, as can oxygen and heat, [3] and [4]. Generally, the main influence on the aging of transformers is exerted by humidity, heat and oxygen, which depends above all on operation conditions to which a transformer has been exposed during its use. The life expectancy of a large power transformers, judging by available estimates, varies between 42 [1] and 50 years [5], provided that it is regularly serviced and spared from major defects that would leave a permanent damage.

3 ASSESSING THE FUTURE UNAVAILABILITY OF NETWORK UNITS

3.1 Observed transmission network units

A transmission network consists of a series of various facilities and devices, or units, components and elements, the most important among them being: overhead lines, cables, substations together with transformers and fields and other equipment, protective devices, measuring devices, telecomska mreža i telekomunikacijska oprema, sustavi vođenja i dr.

Ovaj rad odnosi se na kapitalne jedinice prijenosne mreže, odnosno vodove i transformatore. Promatranje ne ide dublje u podjelu na komponente i pojedine dijelove, već se isti promatraju unutar cjeline, odnosno jedinice mreže.

3.2 Zastoji u prijenosnoj mreži

Najčešće korišteni pokazatelj pouzdanosti prijenosne mreže je njena raspoloživost, odnosno neraspoloživost. Neraspoloživost se definira kao vremenski period unutar promatranog vremenskog razdoblja (najčešće godina dana) unutar kojega mreža, odnosno neka njena jedinica, nije u funkciji.

Poremećaj se definira kao spontano zbivanje u promatranoj mreži u kojem je došlo do prisilnog isklopa barem jednog prekidača, odnosno do prisilnog zastoja barem jedne jedinice prijenosne mreže. Poremećaj započinje kvarom, odnosno događajem kojim neka jedinica prelazi iz ispravnog u neispravno stanje. Otkaz ili ispad definira se kao događaj kojim neka jedinica prisilno prelazi iz pogonskog u izvan pogonsko stanje. Prisilni zastoj je izvan pogonsko stanje promatrane jedinice ostvareno ispadom ili prisilnim isklopom, a neplaniranim ili pogonskim isklopom [6]. S obzirom na uzroke prisilnih zastoja razlikuju se dvije grupe zastoja:

- prisilni zastoj radi unutarnjeg razloga – zastoj radi vlastite neispravnosti,
- prisilni zastoj radi vanjskog razloga – zastoj radi djelovanja zaštite ili isklopom.

Ukoliko je promatrana jedinica u prisilnom zastoju radi vlastite neispravnosti, razlikuje se prisilni zastoj radi unutarnjeg razloga. Ispravna jedinica može biti u prisilnom zastoju ukoliko je izvan pogona radi djelovanja zaštite ili isklopom pa se govori o prisilnom zastoju s vanjskim razlogom. Prisilni zastoj može biti trajan, privremen ili prolazan.

Trajan prisilni zastoj je onaj zastoj koji nastaje radi kvara komponente ili elementa jedinice, nakon čega jedinica nastavlja pogon po otklanjanju kvara. Privremen prisilni zastoj je onaj zastoj kod kojega jedinica nastavlja pogon nakon njenog isklopa bez popravka ili zamjene neke od njezinih komponenata, dok je prolazan prisilni zastoj onaj zastoj kada jedinica nastavlja pogon nakon njenog isklapanja i uspješnog djelovanja APU (automatskog ponovnog uklapanja). Očito je da će starost jedinice imati utjecaj jedino na veličinu trajnih prisilnih zastoja, dok će se privremeni i prolazni prisilni zastoji događati neovisno o starosti promatrane jedinice.

munication network and equipment, control systems, etc.

This work deals with the capital units of a transmission network, i.e., lines and transformers. They are not examined in depth in terms of division into components and parts, they are examined instead within a whole, as network units.

3.2 Outages in the transmission network

The most frequently used indicator of the reliability of a transmission network is its availability and unavailability respectively. Unavailability is defined as a time interval within the observed period of time (mostly one year) when a network or one of its units is out of operation.

Disruption is defined as a spontaneous event within the observed network when a forced disconnection occurs on at least one circuit breaker, or a forced outage of at least one unit of the transmission line. A disruption starts with a failure, an event where a unit passes from a correct into a faulty state. An outage is defined as an event where a unit forcibly passes from an operable into an inoperable state. A forced outage is the out-of-operation condition of the observed unit resulting from sudden outage or forced disconnection, not planned or done intentional [6]. In terms of the causes there are two groups of forced outages:

- forced outage caused by internal reason – outage due to own faultiness,
- forced outage caused by external reason – outage due to a protective action or disconnection.

If the observed unit is in the state of forced outage due to its own faultiness, it is a case of an internal reason. A functional unit may be in the state of forced outage if out of operation due to a protective action or disconnection, so this is a case of a forced outage for an external reason. A forced outage can be permanent, temporary or transient.

A permanent forced outage is one caused by a defective component or element of the unit, after which the unit resumes operation once the defect has been corrected. A temporary forced outage is one where the unit resumes operation after its disconnection without repair or replacement of one of its components. A transient forced outage is one where the unit resumes operation after its disconnection and successful automatic re-closure. It is obvious that the age of the unit will influence only the extent of permanent forced outages, whereas the temporary and transient forced outages will occur aside from the age of the observed unit.

Planirani zastoj je izvan pogonsko stanje promatrane jedinice ostvareno smišljeno, planiranim isklopom, a ne ispadom, radi provođenja neke planirane namjere poput provođenja plana održavanja, otklanjanja nedostataka, preventivne dijagnostike i sličnog [6]. S obzirom na uzroke planiranih zastoja također se razlikuju dvije grupe zastoja:

— planirani zastoj radi unutarnjeg razloga – zastoj radi zahvata na promatranoj jedinici,
— planirani zastoj radi vanjskog razloga – zastoj radi zahvata izvan promatrane jedinice.

Planirani zastoj radi unutarnjeg razloga nastaje ukoliko dolazi do zahvata na promatranoj jedinici, dok planirani zastoj radi vanjskog razloga nastaje ukoliko dolazi do zahvata izvan promatrane jedinice, ali je promatranu jedinicu zbog tog zahvata nužno isključiti.

Starost pojedine jedinice prijenosne mreže utječe i na prisilne i na planirane zastoje, no samo na one s unutarnjim razlogom. Vanjski razlozi za prisilne i planirane zastoje jedinica prijenosne mreže događaju se neovisno o njihovoj starosti, odnosno pogađaju jednakom vjerojatnošću i starije i novije jedinice mreže. Radi starosti jedinice može se očekivati povećani broj prisilnih zastoja radi vlastite neispravnosti jedinice, ali i povećani broj planiranih zastoja s unutarnjim razlogom radi povećanih aktivnosti na održavanju jedinice, otklanjanju nedostataka, dijagnostici i drugom.

Ukoliko se ukupnu neraspoloživost neke jedinice prijenosne mreže označi sa q vrijedi sljedeća relacija:

A planned outage is an out-of-operation state of the observed unit brought about deliberately through planned disconnection, not a breakdown, in order to carry out some planned works, such as implementation of a maintenance schedule, rectification of deficiencies, preventive diagnostics, and similar [6]. In terms of their causes there are two groups of forced outages:

— planned outage caused by internal reason – remedial action on the observed unit,
— planned outage caused by external reason – remedial action outside of the observed unit.

A planned outage caused by internal reason is intended to take a remedial action on the observed unit, whereas a planned outage caused by external reason is undertaken if a remedial action is to take place outside of the observed unit which must be disconnected for that purpose.

The age of a transmission network unit also influences both the forced and the planned outages, but only those with an internal reason. External reasons for forced and planned outages of transmission network units occur aside from their age, and they affect both older and newer network units with equal probability. As a result of the age of a unit an increased number of forced outages can be expected because of the unit's own faultiness, but also an increased number of planned outages for an internal reason, those caused by intensified activities involving maintenance, rectification of deficiencies, diagnostics and other works on the unit.

If the total unavailability of a transmission network unit is marked q, the following relation applies:

$$q = q_{\mathrm{pr}} + q_{\mathrm{pl}} \,, \tag{1}$$

gdje su:

q_{pr} – neraspoloživost radi prisilnih zastoja, a
q_{pl} – neraspoloživost radi planiranih zastoja.

Nadalje vrijedi sljedeće:

where:

q_{pr} – unavailability due to forced outages, and
q_{pl} – unavailability due to planned outages.

Furthermore, the following applies:

$$q_{\mathrm{pr}} = q_{\mathrm{pr\_un}} + q_{\mathrm{pr\_va}} \,, \tag{2}$$

$$q_{\mathrm{pr\_un}} = q_{\mathrm{pr\_un-tr}} + q_{\mathrm{pr\_un-pr}} \,, \tag{3}$$

$$q_{\mathrm{pl}} = q_{\mathrm{pl\_un}} + q_{\mathrm{pl\_va}} \,, \tag{4}$$

$$q = q_{\mathrm{pr\_u}n} + q_{\mathrm{pr\_va}} + q_{\mathrm{pl\_un}} + q_{\mathrm{pl\_va}} \,, \tag{5}$$

gdje su:

- q_{pr_un} – neraspoloživost radi prisilnih zastoja s unutarnjim razlogom,
- $q_{pr\_un\text{-}tr}$ – neraspoloživost radi trajnih prisilnih zastoja s unutarnjim razlogom,
- $q_{pr\_un\text{-}p}$ – neraspoloživost radi privremenih i prolaznih prisilnih zastoja s unutarnjim razlogom,
- q_{pl_va} – neraspoloživost radi prisilnih zastoja s vanjskim razlogom,
- q_{pl_un} – neraspoloživost radi planiranih zastoja s unutarnjim razlogom.

Moguće je generalno utvrditi da starost promatrane jedinice prijenosne mreže utječe na veličine $q_{pr\_un\text{-}r}$ i q_{pl_un}. Budući da se u prisilne zastoje radi unutarnjeg razloga ubrajaju i oni zastoji koji nastaju radi pogonskih prilika i preopterećenja pojedinih jedinica mreže (koja ne ovise o njihovoj starosti), te da se u planirane zastoje radi unutarnjeg razloga ubrajaju i oni zastoji radi redovitog održavanja ili preventivne dijagnostike koji ne trebaju nužno biti povezani sa starošću jedinice u zastoju, teško je naći točnu funkcionalnu ovisnost ove dvije veličine o starosti promatrane jedinice.

Gornja podjela prisilnih i planiranih zastoja koji čine ukupnu neraspoloživost jedinica izvršena je s ciljem procjene buduće neraspoloživosti starijih jedinica mreže, a detaljnom statističkom obradom pogonskih događaja moguće je kvantificirati sve veličine prisilnih i planiranih zastoja te ih razvrstati prema unutarnjim i vanjskim razlozima. Nakon registracije događaja, odnosno ispada neke jedinice ili njenog namjernog isključenja, te identifikacije uzroka tog ispada ili isključenja, moguće je odrediti da li se radi o prisilnom ili planiranom zastoju, je li uzrok zastoju unutarnji ili vanjski, te u slučaju unutarnjeg razloga da li se radi o trajnom ili prolaznom ili privremenom kvaru jedne ili više komponenti.

3.3 Funkcije razdiobe i vjerojatnost zastoja

Zastoji jedinica prijenosne mreže mogu se smatrati slučajnim događajima kojima se pridružuje određena vjerojatnost. Promatraju se jedinice prijenosne mreže i njihova obilježja vezana za prisilne i planirane zastoje te njihove uzroke.

Svakom od tih obilježja može se pridružiti određena vjerojatnost $P(x)$ te pretpostaviti njihove kontinuirane razdiobe na temelju nekih teoretskih distribucija.

Tablica 1 prikazuje jedinice promatranja (jedinice prijenosne mreže), njihova promatrana obilježja (neraspoloživosti radi različitih vrsta zastoja), slučajne varijable te pridružene funkcije vjero-

where:

- q_{pr_un} – unavailability due to forced outages caused by internal reason,
- $q_{pr\_un\text{-}tr}$ – unavailability due to permanent forced outages caused byinternal reason,
- $q_{pr\_un\text{-}p}$ – unavailability due to temporary and transient forced outages caused by internal reason,
- q_{pl_va} – unavailability due to forced outages caused by external reason,
- q_{pl_un} – unavailability due to planned outrages caused by internal reason.

It can be generally ascertained that the age of an observed transmission network unit influences the values $q_{pr\_un\text{-}r}$ and q_{pl_un}. Considering the fact that as forced outages due to an internal reason are also counted the outages caused by operation conditions and overload of some network units (not linked to their age) and that as planned outages for an internal reason are also counted the outages caused by regular maintenance or preventive diagnostics which may not be necessarily linked to the age of the disabled unit, it is hard to find the exact functional dependence of these two values on the age of the observed unit.

The above distribution of the forced and planned outages constituting the overall unavailability of units has been made with a view to assessing the future unavailability of older network units. By detailed statistical processing it is possible to quantify all the values of forced and planned outages and classify them by internal and external causes. Once an event of outage or intentional switching-off of a unit is taken note of and its cause identified, it is possible to determine whether it is a forced or planned outage, whether the cause is internal or external and, if internal, whether it is a case of a permanent or temporary or transient failure on one or more components.

3.3 Distribution functions and the probability of an outage

The outages of transmission network units can be viewed as contingent events accompanied by a certain amount of probability. The units of a transmission network are observed and so are their features associated with forced and planned outages and their causes.

To each of these features a certain probability $P(x)$ is attributable, and, based on some theoretical distributions, their continuous distributions can be presumed.

Table 1 shows the units of observation (transmission network units), their observed features (unavailabilities due to various outages), random variables, jatnosti i razdiobe slučajne varijable. Na temelju statistike pogonskih događaja moguće je odrediti osnovne parametre funkcija razdiobe slučajnih varijabli, i to:

— aritmetičku sredinu $\bar{x}_i$,
— standardnu devijaciju σ_i,

te na temelju tih dviju veličina i ostale parametre traženih funkcija.

associated probability functions and random variable distributions. Based on the statistics of operation events, it is possible to define the basic parameters of the random variable distribution functions, viz.:

— arithmetic mean $\bar{x}_i$,
— standard deviation σ_i,

and, based on these two values, define the other parameters of the related functions.

Tablica 1 – Zastoji jedinica prijenosne mreže, funkcije vjerojatnosti i funkcije razdiobe
Table 1 – Outages of transmission network units, probability functions and distribution functions

Jedinica promatranja / Observed unit	Obilježje jedinice / Unit feature	Slučajna varijabla / Random variable	Funkcija vjerojatnosti / Probability function	Funkcija razdiobe slučajne varijable / Random variable distribution function
Nadzemni vod / Overhead line Kabel / Cable Transformator / Transformer	Neraspoloživost radi trajnih prisilnih zastoja s unutarnjim razlogom / Unavailability due to permanent forced outages caused by internal reason	$q_{\text{pr\_un-tr}}$	$P(q_{\text{pr\_un-tr}})$	$F(q_{\text{pr\_un-tr}})$
	Neraspoloživost radi privremenih i prolaznih prisilnih zastoja s unutarnjim razlogom / Unavailability due to temporary and transient forced outages caused by internal reason	$q_{\text{pr\_un-pr}}$	$P(q_{\text{pr\_un-pr}})$	$F(q_{\text{pr\_un-pr}})$
	Neraspoloživost radi prisilnih zastoja s vanjskim razlogom / Unavailability due to forced outages caused by external reason	$q_{\text{pr\_va}}$	$P(q_{\text{pr\_va}})$	$F(q_{\text{pr\_va}})$
	Neraspoloživost radi planiranih zastoja s unutarnjim razlogom / Unavailability due to planned outages caused by internal reason	$q_{\text{pl\_un}}$	$P(q_{\text{pl\_un}})$	$F(q_{\text{pl\_un}})$
	Neraspoloživost radi planiranih zastoja s vanjskim razlogom / Unavailability due to planned outages caused by external reason	$q_{\text{pl\_va}}$	$P(q_{\text{pl\_va}})$	$F(q_{\text{pl\_va}})$

U teoriji pouzdanosti mreža najčešće korištene teoretske funkcije vjerojatnosti i funkcije razdiobe slučajne varijable su normalna razdioba i Weibullova razdioba [7]. Normalna razdioba određena je aritmetičkom sredinom i standardnom devijacijom (6), dok je Weibullova razdioba (7) određena parametrima oblika i mjere (k i λ) koje je također moguće odrediti na temelju poznate aritmetičke sredine i standardne devijacije [8]:

In the theory of network reliability the most often used theoretical probability functions and random variable distribution functions are the normal distribution and the Weibull distribution [7]. The normal distribution is defined by the arithmetic mean and the standard deviation (6), whereas the Weibull distribution (7) is defined by the shape and scale (k and λ) parameters which can also be defined on the basis of a known arithmetic mean and standard deviation [8]:

$$F(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-(x-\bar{x})^2}{2\sigma^2}}, \qquad (6)$$

$$F(x,k,\lambda) = \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} e^{-(\frac{x}{\lambda})^k}. \qquad (7)$$

3.3 Metoda za procjenu neraspoloživosti jedinica mreže u kratkoročnom razdoblju

Kako je prethodno objašnjeno nije moguće univerzalno i jednoznačno naći funkcionalnu ovisnost neraspoloživosti jedinica prijenosne mreže i njihove starosti. U razdoblju normalnog korištenja jedinice njena neraspoloživost je približno konstantna, odnosno ne ovisi o starosti promatrane jedinice. Unutar razdoblja dotrajalosti funkcionalna ovisnost može biti snažna budući da se neraspoloživost jedinice značajno povećava s njenom starosti, ali ju je i dalje nemoguće jednoznačno odrediti.

Definirana metoda za procjenu buduće neraspoloživosti jedinica prijenosne mreže temelji se na podacima o zastojima jedinica i njihovim uzrocima iz statistike pogonskih događaja, te određivanju vjerojatnosti zastoja u promatranom budućem kratkoročnom razdoblju pretpostavljajući da se određene vrste zastoja (funkcionalno ovisne o starosti promatrane jedinice) distribuiraju na temelju poznatih teoretskih funkcija razdiobe slučajne varijable (normalna razdioba i Weibull-ova razdioba).

Procjena kratkoročne neraspoloživosti promatranih jedinica prijenosne mreže (vodova i transformatora) vrši se na sljedeći način:

— za vodove i transformatore mlađe od 40 godina (ili neke druge postavljene granice) pretpostavlja se konstantna neraspoloživost radi prisilnih i planiranih zastoja, te konstantna ukupna neraspoloživost, jednaka odgovarajućim prosjecima (aritmetičkim sredinama) za razdoblje obuhvaćeno statistikom pogonskih događaja:

3.3 Method of estimating the unavailability of network units in a short-term period

As explained above, there is no universal and clear-cut way of finding the functional dependence of the unavailability of transmission network units and their age. In a period of normal use the unavailability of a unit is approximately constant in that it does not depend on the age of the observed unit. Within a period of deteriorated condition the functional dependence may be strong because the unavailability of a unit is significantly increasing with its age, but it continues to defy a clear-cut definition.

The defined method of estimating the future unavailability of transmission network units is based on data concerning the outages of the units and their causes taken from the statistics on operation events and on the definition of outage probability in the observed future short-term period, provided that certain types of outages (functionally dependent on the age of the observed unit) are distributed in conformity with the known theoretical random variable distribution functions (the normal distribution and the Weibull distribution).

The short-term unavailability of observed transmission network units (lines and transformers) is assessed as follows:

— for lines and transformers younger than 40 years (or some other set limit) a constant unavailability is assumed due to forced and planned outages, as well as constant overall unavailability, equal to the corresponding averages (arithmetic means) for a period covered by the statistics of operation events:

$$q_{\mathrm{pr}} = \frac{1}{N} \cdot \sum_{n=1}^{N} q_{\mathrm{pr},n} , \tag{8}$$

$$q_{\mathrm{pl}} = \frac{1}{N} \cdot \sum_{n=1}^{N} q_{\mathrm{pl},n} , \tag{9}$$

gdje je:

- N – ukupan broj godina obuhvaćenih statistikom pogonskih događaja,
- $q_{\mathrm{pr},n}$ – neraspoloživost radi prisilnih zastoja u n-toj godini promatranja, a
- $q_{\mathrm{pl},n}$ – neraspoloživost radi planiranih zastoja u n-toj godini promatranja.

Za ovu grupu promatranih jedinica prijenosne mreže ne razlikuju se prisilni i planirani zastoji radi unutarnjih i vanjskih razloga, tako ni prisilni

where:

- N – total number of years covered by the statistics of operation events,
- $q_{\mathrm{pr},n}$ – unavailability due to forced outages in the n-th observation year, and
- $q_{\mathrm{pl},n}$ – unavailability due to planned outages in the n-th observation year.

For this group of observed transmission network units there is no difference between the forced and the planned outages due to internal and external zastoji radi unutarnjih razloga prema istrajnosti (trajni, prolazni, privremeni), budući da se pretpostavlja kako se isti nalaze u razdoblju normalnog korištenja kada nije vidljiva funkcionalna veza između određenih vrsti zastoja i starosti jedinice mreže.

— za kandidate starije od 40 godina u promatranom trenutku pretpostavlja se sljedeće:

  - u razmatranom kratkoročnom razdoblju neće doći do trajnog isključenja niti jedne promatrane jedinice mreže (nije trajan kvar, odnosno uništenje),
  - starost jedinice ima posljedice samo na prisilne i planirane zastoje radi unutarnjih razloga, a unutar prisilnih zastoja radi unutarnjih razloga samo na trajne prisilne zastoje,
  - prisilni i planirani zastoji radi vanjskih razloga, te prolazni i privremeni prisilni zastoji radi unutarnjih razloga, ne ovise o starosti promatrane jedinice,
  - neraspoloživosti jedinice zbog trajnih prisilnih i planiranih zastoja radi unutarnjih razloga opisuju se svaka svojom funkcijom razdiobe (normalne ili Weibullove),
  - srednje vrijednosti i standardne devijacije uzorka neraspoloživosti jedinica zbog trajnih prisilnih i planiranih zastoja s unutarnjim razlogom u razdoblju obuhvaćenom statistikom pogonskih događaja definiraju funkciju normalne razdiobe ili funkciju Weibullove razdiobe na temelju koje se procjenjuje kratkoročna neraspoloživost jedinica zbog trajnih prisilnih zastoja radi unutarnjih razloga i neraspoloživost jedinica zbog planiranih zastoja radi unutarnjih razloga,
  - postavlja se vjerojatnost od 0,95 da će procijenjene vrijednosti neraspoloživosti radi trajnih prisilnih i planiranih zastoja s unutarnjim razlogom poprimiti vrijednosti u intervalu od 0 do procijenjene vrijednosti neraspoloživosti, a iz razloga sigurnosti za procijenjenu vrijednost neraspoloživosti radi trajnih prisilnih i planiranih zastoja s unutarnjim razlogom uzimamo gornju granicu intervala,
  - procijenjene buduće neraspoloživosti radi prolaznih i privremenih prisilnih zastoja s unutarnjim razlogom, te prisilnih i planiranih zastoja s vanjskim razlogom, jednake su srednjoj vrijednosti uzorka istovrsnih neraspoloživosti iz statistike pogonskih događaja.

Neraspoloživosti radi privremenih i prolaznih prisilnih zastoja s unutarnjim razlogom ($q_{pr\_un\text{-}p}$), neraspoloživosti radi prisilnih zastoja s vanjskim razlogom (q_{pr_va}) i neraspoloživosti radi planiranih

reasons, nor the forced outages for internal reasons according to the degree of persistence (permanent, transient, temporary), since it is assumed that they take place in the periods of normal use when the functional link between certain types of outages and the age of a network unit is not obvious.

— For candidates older than 40 years at an observed juncture the following is presumed:

  - over the observed short-term period there will be no permanent disconnection of any observed network unit (it is not a permanent defect or a destruction),
  - the age of the unit concerned has affects only the forced and planned outages caused by internal reasons, and within the forced outages caused by internal reasons only the permanent forced outages,
  - the forced and planned outages caused by external reasons, and the transient and temporary forced outages caused by internal reasons, are independent of the age of the observed unit,
  - the unavailabilities of a unit due to permanent forced and planned outages caused by internal reasons are each described with its distribution function (normal or Weibull),
  - the mean values and standard deviations of an unavailability sample of units due to permanent forced and planned outages caused by internal reason in the period covered by the statistics of operation events define the normal distribution function or the Weibull distribution function, on the basis of which the short-term unavailability of units due to permanent forced outages caused by internal reasons and the unavailability of units due to planned outages caused by internal reasons are assessed,
  - a probability of 0.95 is set that the assessed unavailability values due to permanent forced and planned outages caused by internal reason will assume values in an interval from 0 to the assessed unavailability value, whereas, to be on the safe side, for the assessed unavailability value due to permanent forced and planned outages caused by internal reason the upper limit of the interval is taken
  - the assessed future unavailabilities due to transient and temporary forced outages caused by internal reason, and forced and planned outages caused by external reason, equal the mean value of the sample of unavailabilities of the same type taken from the statistics of operation events.

The unavailabilities due to temporary and transient forced outages caused by internal reason ($q_{pr\_un\text{-}p}$), the unavailabilities due to forced outages caused by zastoja s vanjskim razlogom (q_{pl_va}) ne ovise o starosti voda pa se računaju kao:

external reason (q_{pr_va}) and the unavailabilities due to planned outages caused by external reason (q_{pl_va}) are independent of the age of the line, so they are calculated as:

$$q_{pr\_un-pr} = \frac{1}{N} \cdot \sum_{n=1}^{n=N} q_{pr\_un-pr,n} \quad , \tag{10}$$

$$q_{pr\_va} = \frac{1}{N} \cdot \sum_{n=1}^{n=N} q_{pr\_va,n} \quad , \tag{11}$$

$$q_{pl\_va} = \frac{1}{N} \cdot \sum_{n=1}^{n=N} q_{pl\_va,n} \quad , \tag{12}$$

gdje je:

- $q_{pr\_un-pr,n}$ – neraspoloživost radi privremenih i prolaznih prisilnih zastoja s unutarnjim razlogom u godini n,
- $q_{pr\_va,n}$ – neraspoloživost radi prisilnih zastoja s vanjskim razlogom u godini n,
- $q_{pl\_va,n}$ – neraspoloživost radi planiranih zastoja s vanjskim razlogom u godini n, te ostaju konstantne za promatrano buduće razdoblje.

Srednje vrijednosti neraspoloživosti radi trajnih prisilnih i planiranih zastoja radi unutarnjih razloga iznose:

where:

- $q_{pr\_un-pr,n}$ – unavailability due to temporary and transient forced outages caused by internal reason in year n,
- $q_{pr\_va,n}$ – unavailability due to forced outages caused by external reason in year n,
- $q_{pl\_va,n}$ – unavailability due to planned outages caused by external reason in year n, remaining constant for the observed future period.

The mean values of unavailability due to permanent forced and planned outages caused by internal reasons amount to:

$$q_{pr\_un-tr} = \frac{1}{N} \cdot \sum_{n=1}^{n=N} q_{pr\_un-tr,n} \quad , \tag{13}$$

$$q_{pl\_un} = \frac{1}{N} \cdot \sum_{n=1}^{n=N} q_{pl\_un,n} \quad , \tag{14}$$

gdje je:

- $q_{pr\_un-tr,n}$ – neraspoloživost radi trajnih prisilnih zastoja s unutarnjim razlogom u godini n,
- $q_{pl\_un,n}$ – neraspoloživost radi planiranih zastoja s unutarnjim razlogom u godini n.

Standardne devijacije neraspoloživosti radi prisilnih i planiranih zastoja s unutarnjim razlogom iznose:

where:

- $q_{pr\_un-tr,n}$ – unavailability due to permanent forced outages caused byinternal reason in year n,
- $q_{pl\_un,n}$ – unavailability due to planned outages caused byinternal reason in year n.

Standard deviations of unavailability due to forced and planned outages caused by internal reason amount to:

$$\sigma_{\mathrm{pr\_un-tr}} = \sqrt{\frac{\sum_{n=1}^{n=N} (q_{\mathrm{pr\_un-tr},n} - q_{\mathrm{pr\_un-tr}})^2}{(N-1)}} \, , \quad (15)$$

$$\sigma_{\mathrm{pl\_un}} = \sqrt{\frac{\sum_{n=1}^{n=N} (q_{\mathrm{pl\_un},n} - q_{\mathrm{pl\_un}})^2}{(N-1)}} \, , \quad (16)$$

gdje je N veličina uzorka (broj godina obuhvaćenih statistikom pogonskih događaja).

Funkcija normalne razdiobe definirana je izrazom (6), dok je vjerojatnost da varijabla x poprimi neku vrijednost iz intervala $[x_1, x_2]$ definirana sljedećim izrazom:

where N is the sample size (number of years covered by the statistics of operation events).

The normal distribution function is defined by the expression (6), whereas the probability of variable x to assume some value from the interval $[x_1, x_2]$ is defined by the following expression:

$$P(x_1 < x < x_2) = \int_{x_1}^{x_2} F(x) \cdot \mathrm{d}x = \int_{x_1}^{x_2} \frac{1}{\sigma\sqrt{2\pi}} \mathrm{e}^{\frac{-(x-\bar{x})^2}{2\sigma^2}} \cdot \mathrm{d}x \, . \quad (17)$$

Kod Weibullove razdiobe funkcija razdiobe definirana je izrazom (7), a vjerojatnost da varijabla x poprimi vrijednost iz intervala $[x_1, x_2]$ računa se preko sljedećeg izraza:

With the Weibull distribution the distribution function is defined by the expression (7), whereas the probability of variable x to assume some value from the interval $[x_1, x_2]$ is calculated by the following expression:

$$P(x_1 < x_i \leq x_2) = \int_{x_1}^{x_2} P(x_i) \cdot \mathrm{d}x = F(x_2) - F(x_1) \, . \quad (18)$$

Ako se označi sljedeće:

If the following is denoted:

$$x = q_{\mathrm{pr-Un-tr},n} \quad (19a)$$

ili

or

$$q_{\mathrm{pl\_un},n} \quad (19b)$$

u budućem razdoblju

in the future period

$$\bar{x} = q_{\mathrm{pr\_un-tr}} = \frac{1}{N} \cdot \sum_{n=1}^{n=N} q_{\mathrm{pr\_un-tr},n} \quad (20a)$$

ili

or

$$q_{\text{pl\_un}} = \frac{1}{N} \cdot \sum_{n=1}^{n=N} q_{\text{pl\_un},n} \ . \qquad (20b)$$

Iterativnim putem moguće je naći vrijednost x za koju je vjerojatnost prema funkciji normalne razdiobe jednaka zadanoj vrijednosti, npr. $P(x) = 0,95$. Tada je vrijednost x jednaka predviđenoj neraspoloživosti razmatrane jedinice mreže radi trajnih prisilnih, odnosno planiranih zastoja s unutarnjim razlogom u budućoj razmatranoj godini.

Ukoliko se koristi Weibullova razdioba iz aritmetičke sredine uzorka i standardne devijacije izračunavaju se parametri razdiobe k i λ, te se pomoću inverzne Weibullove funkcije izračunava vrijednost x koja odgovara zadanoj vjerojatnosti, na pr. $P(x) = 0,95$. Tada je, kao i u prethodnom slučaju, vrijednost x jednaka predviđenoj neraspoloživosti razmatrane jedinice mreže radi trajnih prisilnih, odnosno planiranih zastoja s unutarnjim razlogom u budućoj razmatranoj godini.

Ukupna procijenjena neraspoloživost razmatranih jedinica jednaka je sumi procijenjenih neraspoloživosti radi prisilnih i planiranih zastoja zbog unutarnjih i vanjskih razloga.

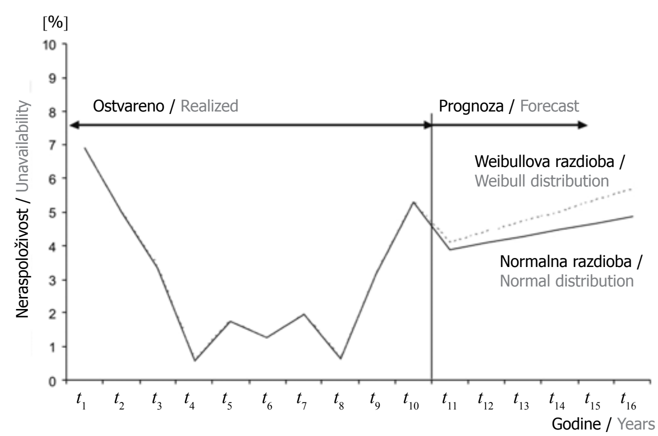
Nakon što se izračunaju iznosi neraspoloživosti radi prisilnih i planiranih zastoja s unutarnjim razlozima u prvoj budućoj godini ta se vrijednost pridruži osnovnom skupu (uzorku), opet se računa srednja vrijednost skupa i standardna devijacija iz čega se dobije procjena odgovarajuće neraspoloživosti za iduću godinu promatranja. Postupak se ponavlja sve dok nije obuhvaćeno čitavo buduće razdoblje promatranja. Primjer određivanja neraspoloživosti na opisani način prikazan je slikom 2.

then it is iteratively possible to find the value x for which the probability according to the normal distribution function equals the given value, e.g., $P(x) = 0,95$. Then the value x equals the anticipated unavailability of the observed network unit due to permanent or planned outages caused by internal reason in the future observed year.

If the Weibull distribution is used, the distribution parameters k and λ are obtained from the arithmetic mean of the sample and the standard deviation, and by means of the inverse Weibull function the value x is calculated which corresponds to the given value, e.g., $P(x) = 0,95$. Then, like in the previous case, the value x equals the anticipated unavailability of the observed network unit due to permanent forced or planned outages caused by internal reason in the future observed year.

The total assessed unavailability of studied units equals the sum of assessed unavailabilities due to forced and planned outages caused by internal and external reasons.

Once the amounts of unavailability due to forced and planned outages in the first future year have been calculated, that value is attached to the basic set (sample), the mean value of the basic set, the mean value of the set and the standard deviation are again calculated, from which an assessment of the corresponding unavailability for the next observation year is obtained. The procedure is repeated until the whole future observation period is covered. Figure 2 below gives an example of how unavailability is defined in the described way.



Slika 2 — Procjena buduće neraspoloživosti voda starijeg od 40 godina (Weibullova)
Figure 2 — Assessment of the future unavailability of a line older than 40 years (Weibull distribution)

4 PROBABILISTIČKE SIMULACIJE RADA EES-a

Korištena probabilistička simulacija (Monte-Carlo) zasniva se na stohastički modeliranim ulaznim podacima, velikom broju proračuna istosmjernih optimalnih tokova snaga i odgovarajućim optimizacijskim algoritmom za određivanje minimalne redukcije opterećenja elemenata mreže (vodova i transformatora).

U pripremi podataka za proračun prikupljaju se osnovni parametri jedinica prijenosne mreže, statistički se obrađuju podaci o njihovoj raspoloživosti iz statistike pogonskih događaja, vrši se procjena njihove neraspoloživosti u promatranom budućem razdoblju, zatim se određuje očekivana vrijednost vršnog opterećenja sustava i pripadna standardna devijacija, oblik godišnje krivulje trajanja opterećenja te struktura i parametri sadašnjih i budućih proizvodnih postrojenja.

Prijenosna mreža je definirana topologijom, odnosno popisom čvorišta i grana. Svaka grana je određena svojom uzdužnom impedancijom (r, x), neraspoloživošću (q) i maksimalno dozvoljenim strujom u normalnim (I_{max}) i izvanrednim uvjetima ($I_{max\,20}$).

Opterećenje i potrošnja po svakom čvorištu definirana je vršnim opterećenjem (snagom) i oblikom godišnje krivulje trajanja opterećenja koja se opisuje nizom koeficijenata. Zbog pojednostavljenja, a da se ne gubi fizikalni smisao, u daljnjim analizama pretpostavlja se da je oblik krivulje jednak za sva čvorišta u mreži. Očekivana vrijednost vršnog opterećenja rezultat je posebnih studija u kojima se promatra niz faktora koji utječu na potrošnju električne energije (bruto društveni proizvod, udio pojedinih gospodarskih sektora u stvaranju domaćeg proizvoda, utjecaj energetski intenzivne industrije, struktura i karakteristike trošila i drugo). Standardnom devijacijom uzimaju se u obzir nesigurnosti u predviđanju, utjecaj klimatskih faktora te nesigurnosti u priključku novih potrošača na mrežu. Godišnja krivulja trajanja opterećenja dijeli se na određeni broj dijelova konstantnog opterećenja (P) i vremena trajanja (t).

Svaka proizvodna termo jedinica modelira se maksimalnom snagom, raspoloživošću i prosječnim pogonskim troškovima. Hidroelektrane se dijele na dvije kategorije: protočne (njihova proizvodnja ovisna je o pretpostavljenoj hidrologiji), te akumulacijske (njihov angažman je promjenljiv, a ovisi o hidrologiji i načinu upravljanja akumulacijama).

Za prvu vrstu hidroelektrana zadaje se angažirana snaga koja tijekom proračuna ostaje konstantna,

4 PROBABILISTIC SIMULATIONS OF THE EPS OPERATION

The used probabilistic simulation (Monte-Carlo) is based on stochastically modeled input data, a great number of DC optimal power flow calculations and appropriate optimization algorithms for defining the minimum load reduction for the network elements (lines and transformers).

In preparing data for calculation, the basic parameters of the transmission network units are collected, data on their availability, taken from the statistics of operation events, are processed and their unavailability over the future observed period is assessed, which is followed by the definition of the expected peak load value of the system and the pertaining standard deviation, the shape of the annual load duration curve and the structure and parameters of the present and future generation facilities.

The transmission network is defined by the topology or the list of nodes and branches. Each branch is determined by its impedance (r, x), unavailability (q) and the maximum permitted electric current under normal (I_{max}) and emergency conditions ($I_{max\,20}$).

The load and demand per each node is defined by the peak load (power) and shape of the annual load duration curve described by a series of coefficients. For the sake of simplicity, but without losing the physical meaning of it, in the succeeding analyses it is assumed that the shape of the curve is equal for all nodes in the network. The expected peak load value is a result of special studies in which a series of factors are investigated, those influencing electricity consumption (gross social product, the share of special industrial sectors in the creation of domestic product, the impact of energy-intensive industry, the structure of energy users, etc.). With the standard deviation the uncertainties in forecasting, the impact of climatic factors and the uncertainties involved in the connection of new consumers to the network are taken into account. The annual load duration curve is divided into a certain number of parts of the constant load (P) and duration times (t).

Each thermal generation unit is modeled by maximum power, availability and average operating costs. Hydro power plants are divided into two categories: the run-of-river (output dependent on the assumed hydrology) and the storage power plants (with changeable engagement, depending on the local hydrology and storage management).

For the former type of hydro power plants engaged power is given which remains constant during the calculation, whereas given for the latter type dok se za drugi tip hidroelektrana zadaje maksimalna snaga i početno angažirana snaga koja se određuje na osnovi načina upravljanja akumulacijama i za koju su troškovi proizvodnje jednaki nuli. Radi dodatnog angažiranja akumulacijskih hidroelektrana s ciljem otklanjanja mogućih poremećaja u mreži pri pojedinim uklopnim stanjima definira se trošak dodatne hidro proizvodnje, koji u principu određuje način pražnjenja akumulacija.

Nakon određivanja stanja izgrađenosti proizvodnih postrojenja i troškova njihove proizvodnje (uzimaju se u obzir samo varijabilni troškovi) vrši se proračun istosmjernih optimalnih tokova snaga, odnosno rješava se optimizacijski problem:

are maximum power and initially engaged power which is defined on the basis of the way in which storages are run and for which the generation cost equals zero. For additional engagement of storage hydro plants with a view to eliminating possible network congestions in some operation conditions, the cost of additional hydro generation is defined, which in principle determines the method of storages management.

After ascertaining the constructed status of generation facilities and the costs of their power output (only the variable costs are taken into account), the DC optimal power flows are calculated. i.e., the optimization problem is being resolved:

$$\mathrm{Min}\ \left[\sum_i C_i(P_{\mathrm{G}i}) + \mu \sum_i H_i + \sum_i c_i P^{\mathrm{r}}_{\mathrm{D}i}\right], \tag{21}$$

$$P_{\mathrm{G}i\min} \leq P_{\mathrm{G}i} \leq P_{\mathrm{G}i\max}\ , \tag{22}$$

$$0 \leq H_i \leq H_{i\max}\ , \tag{23}$$

$$[\boldsymbol{B}]\cdot[\theta_i] - [\boldsymbol{P}_{\mathrm{G}i}] = [-\boldsymbol{P}_{\mathrm{D}i}]\ , \tag{24}$$

$$\frac{1}{x_{ij}}\left(\theta_i - \theta_j\right) + s_{ij} = P_{ij}^{\max}\ , \tag{25}$$

$$0 \leq P^{\mathrm{r}}_{\mathrm{D}i} \leq P_{\mathrm{D}i}\ , \tag{26}$$

gdje su:

- $C_i(P_{\mathrm{G}i})$ – funkcija troškova proizvodnje generatora (ponuda generatora na tržištu)
- $P_{\mathrm{G}i}$ – djelatna snaga generatora u čvoru i
- $P_{\mathrm{D}i}$ – iznos tereta (opterećenja) u čvoru i
- $P^{\mathrm{r}}_{\mathrm{D}i}$ – iznos reduciranog opterećenja u čvoru i
- $P_{\mathrm{G}i\,\mathrm{mix}}$ – minimalna snaga generatora u čvoru i
- $P_{\mathrm{G}i\,\max}$ – maksimalna snaga generatora u čvoru i
- θ_i, θ_j – kutovi napona u čvorovima i i j
- S_{ij} – dodatna varijabla u granicama 0-2$P_{ij}^{\max}$
- $P_{ij}^{\max}$ – maksimalno dozvoljena djelatna snaga vodom između čvorova i, j
- H_i – dodatna hidro proizvodnja u čvorištu i,
- $H_{i\max}$ – maksimalna hidro proizvodnja u čvorištu i,
- μ – jedinični troškovi dodatne hidro proizvodnje,

where:

- $C_i(P_{\mathrm{G}i})$ – cost function of generator output (generator's bids on the market)
- $P_{\mathrm{G}i}$ – generator's active power in node i
- $P_{\mathrm{D}i}$ – amount of load in node i
- $P^{\mathrm{r}}_{\mathrm{D}i}$ – amount of reduced load in node i
- $P_{\mathrm{G}i\,\mathrm{mix}}$ – generator's minimum power in node i
- $P_{\mathrm{G}i\,\max}$ – generator's maximum power in node i
- θ_i, θ_j – voltage angles in nodes i and j
- S_{ij} – additional variable within margins 0-2$P_{ij}^{\max}$
- $P_{ij}^{\max}$ – maximum permissible active power by line between nodes i, j
- H_i – additional hydro generation in node i,
- $H_{i\max}$ – maximum hydro generation in node i,
- μ – unit costs of additional hydro generation,
- c_i – unit price of undelivered electricity in node i.

c_i – jedinični trošak neisporučene električne energije u čvoru i.

Topološka se nesigurnost (uklopno stanje generatora, vodova i transformatora) uzima u obzir korištenjem generatora pseudoslučajnih brojeva uniformne razdiobe koji se koriste za svaku jedinicu mreže (ukoliko je pseudoslučajni broj u intervalu $[0, p_{ij}]$ vod/transformator je u pogonu, ukoliko je pseudoslučajni broj u intervalu $(p_{ij}, 1]$ vod/transformator je izvan pogona, pri čemu je p_{ij} raspoloživost promatranog elementa ($p_{ij} = 1 - q_{ij}$); analogan je postupak za generatore). Prema tome, u svakoj simulaciji potrebno je generirati matricu susceptancija čvorova $\boldsymbol{B}$ sa slučajno određenim elementima ovisno o uklopnom stanju grana mreže.

Za svaki aproksimirani dio godišnje krivulje trajanja opterećenja izvodi se velik broj proračuna istosmjernih optimalnih tokova snaga, te se izračunavaju sljedeće prosječne vrijednosti:

— matematičko očekivanje godišnje neisporučene električne energije i
— troškovi neisporuke električne energije,
— ukupni troškovi proizvodnje elektrana u sustavu,
— ukupni operativni troškovi rada sustava,
— procjena očekivanog marginalnog smanjenja godišnje neisporučene električne energije pri povećanju kapaciteta svake grane u mreži za 1 MW.

Dobivene rezultate moguće je razvrstati prema uzroku nastanka:

— troškovi uzrokovani nedostatkom proizvodnih postrojenja, te
— troškovi uzrokovani ograničenjima u mreži.

Od interesa za ovaj rad samo su ona ograničenja uzrokovana slabostima mreže. Najvažnije veličine na temelju kojih se u kasnije opisanoj metodologiji određuje lista prioriteta za zamjene i rekonstrukcije ukupni su godišnji očekivani troškovi neisporučene električne energije uzrokovani slabostima mreže, te ukupni godišnji očekivani troškovi preraspodjele angažmana elektrana (u odnosu na minimalne troškove proizvodnje do kojih bi došlo ukoliko u mreži ne bi bilo ograničenja niti u jednom ispitanom pogonskom stanju) uzrokovani slabostima mreže.

Da bi se izbjeglo stohastičko modeliranje većeg broja ulaznih veličina moguće je primijeniti multiscenarijsku analizu kod koje se definira više mogućih i realnih scenarija s obzirom na neku ulaznu veličinu, a zatim se vrše probabilističke simulacije za svaki scenarij i izračunavaju prosječne izlazne vrijednosti varijabli od interesa. Ukoliko su pozna-

The topological uncertainty (the switching status of generators, lines and transformers) is taken into consideration by using generators of pseudo-random numbers of uniform distribution which are used for each network unit (if a pseudorandom number is in the interval $[0, p_{ij}]$ the line/transformer is in operation, if a pseudo-random number is in the interval $(p_{ij}, 1]$ line/transformer is out of operation, where p_{ij} is the availability of the observed element ($p_{ij} = 1 - q_{ij}$). The procedure is analogous for the generators). Therefore, in each simulation it is necessary to generate a susceptance matrix of nodes $\boldsymbol{B}$ with randomly defined elements in dependence on the switching status of network branches.

For each approximated part of the annual load duration curve a great number of DC optimal power flows calculations is performed, and the following average values are being computed:

— mathematically expected annual undelivered electricity,
— costs of undelivered electricity,
— total generation costs of power plants in the system,
— total operating costs of the system's operation,
— estimated expected marginal decrease in annually undelivered electricity with a capacity increase of every branch in the network by 1 MW.

The obtained results can be classified as follows:

— costs caused by the lack of generation facilities, and
— costs caused by network constraints.

Of interest for the present work are only the constraints caused by the network's weaknesses. The most important values based on which a priority list of replacements and reconstructions is compiled by means of the below described methodology are the total annual expected costs of undelivered electricity caused by the network's weaknesses and the total annual expected costs of power plants re-dispatch (relative to the minimum generation costs incurred if there were no constraints in the network in any tested operation state) caused by the network's weaknesses.

In order to avoid the stochastic modeling of a greater number of input values, it is possible to apply the multi-scenario analysis where a number of possible and real scenarios are defined relative to some input value and then probabilistic simulations are made for each scenario, and average output values of interest are computed. If the onset probabilities of particular scenarios (P_j, $j = 1, 2, ..., P_j$, M_s, where M_s is the total number te vjerojatnosti nastanka pojedinačnih scenarija (P_j, $j = 1, 2, ..., P_j$, M_s, gdje je M_s ukupni broj scenarija), tražena srednja vrijednost varijable x izračunava se kao suma umnožaka izračunatih vrijednosti x u svakom scenariju i vjerojatnosti nastanka tog scenarija:

of scenarios) are known, the sought mean value of variable x is calculated as a sum of the products of the calculated values x in each scenario and the onset probabilities of that scenario:

$$\bar{x} = \sum_{j=1}^{M_s} p_j x_j \; . \tag{27}$$

5 KRITERIJI ZA REVITALIZACIJU VODOVA I TRANSFORMATORA

5.1 Metoda za ocjenu uloge i važnosti jedinica u prijenosnoj mreži

Uloga pojedinih vodova i transformatora u prijenosnoj mreži (elektroenergetskom sustavu) određuje se multi-scenarijskom analizom i probabilističkim simulacijama rada sustava. Unutar probabilističkih simulacija stohastički se modelira samo neraspoloživost pojedinih grana i generatora, odnosno promatra se samo topološka nesigurnost, budući da je ona od najvećeg interesa za određivanje liste prioriteta za revitalizaciju vodova i transformatora. Ostale vrste nesigurnosti (poput plana izgradnje novih elektrana, hidroloških okolnosti i dr.) modeliraju se kroz multi-scenarijsku analizu. Na osnovi izračuna operativnih troškova rada elektroenergetskog sustava tijekom cjelokupne godišnje krivulje trajanja opterećenja unutar promatranog kratkoročnog razdoblja određuje se utjecaj različitih razina neraspoloživosti promatranih vodova i transformatora na troškove rada sustava. Pri ocjeni uloge jedinica prijenosne mreže promatraju se svi definirani scenariji koji mogu biti ovisni o vremenskom presjeku, izgradnji novih elektrana, ponudama proizvođača, hidrološkim prilikama, bilanci sustava i drugim nesigurnostima unutar promatranog vremenskog razdoblja.

U svim analiziranim scenarijima pogona sustava za svaki se vod i transformator – kandidat za zamjene i rekonstrukcije, promatra pet razina njegove buduće neraspoloživosti, te se za svaku izračunava povećanje očekivanih godišnjih operativnih troškova rada EES-a radi slabosti u mreži:

— prosječna (vodovi i transformatori mlađi od 40 godina) ili procijenjena neraspoloživost vodova i transformatora (stariji od 40 godina), određene metodom opisanom u poglavlju 3,

5 CRITERIA FOR THE REVITALIZATION OF LINES AND TRANSFORMERS

5.1 The method of estimating the role and importance of units in the transmission network

The role of individual lines and transformers in a transmission network (EPS) is defined by the multi-scenario analysis and probabilistic simulations of the system's operation. Within the probabilistic simulations only the unavailability of individual branches and generators is stochastically modeled, i.e., only the topological uncertainty is observed, because it is of the greatest interest for compiling the priority list for the revitalization of lines and transformers. Other types of uncertainty (like a plan for the construction of new power plants, the factor of hydrological conditions, etc.) are modeled by using the multi-scenario analysis. Based on the calculated operating costs of the EPS during the entire annual load duration curve within an observed short-term period, the impact of different availability levels of the observed lines and transformers on the system's operating costs is determined. In assessing the role of the transmission network units, all the scenarios are observed that may depend on the time cross-section, the construction of new power plants, the generators' bids, the hydrological conditions, the system's balance and other uncertainties within the observed period of time.

In all the analyzed system operation scenarios, for each line and transformer – revitalization candidate, five levels of its future unavailability are observed and for each an increase in the expected annual operating costs of the EPS, due to weaknesses in the network, is calculated:

— the average (lines and transformers younger than 40 years) or estimated unavailability of lines and transformers (older than 40 years), defined by the method described in Section 3,

— prosječna neraspoloživost svih vodova i transformatora (pa i onih starijih od 40 godina), na temelju statistike pogonskih događaja,
— reducirana neraspoloživost vodova i transformatora starijih od 40 godina nakon izvođenja revitalizacije, pri čemu se neraspoloživost pojedinačnih kandidata određuje uz pretpostavku idealnog smanjenja na nulu trajnih prisilnih i planiranih zastoja s unutarnjim razlogom,
— trajna neraspoloživost voda ili transformatora (neraspoloživost 100 %),
— potpuna raspoloživost voda ili transformatora (neraspoloživost 0 %).

Uloga pojedinog voda ili transformatora ocjenjuje se na temelju razlika troškova rada sustava uzrokovanih slabostima u mreži za pojedine ispitivane razine raspoloživosti promatranih vodova i transformatora. Za ocjenu uloge pojedinih vodova i transformatora uvode se sljedeće oznake:

$MC_{i,\mathrm{k}}(j)$: marginalna dobit od povećanja kapaciteta voda ili transformatora k (smanjenje operativnih troškova rada EES-a pri povećanju prijenosne moći voda ili prividne snage transformatora k za 1 MW) u i-toj godini, za j-ti analizirani scenarij, uz procijenjenu neraspoloživost vodova i transformatora u mreži.

$OC_i(j)$: godišnji operativni troškovi rada sustava uzrokovani slabostima u mreži u i-toj godini za j-ti analizirani scenarij ovisan o modeliranim nesigurnostima, uz procijenjenu neraspoloživost vodova i transformatora u mreži.

$OC_{i,\mathrm{k}}(j)$: godišnji operativni troškovi rada sustava uzrokovani slabostima u mreži u i-toj godini za j-ti analizirani scenarij uz neraspoloživost voda ili transformatora k jednaku prosječnoj vrijednosti u proteklom razdoblju obuhvaćenim statistikom pogonskih događaja.

$OC'_{i,\mathrm{k}}(j)$: godišnji operativni troškovi rada sustava uzrokovani slabostima u mreži u i-toj godini za j-ti analizirani scenarij uz neraspoloživost voda ili transformatora k jednaku prosječnoj vrijednosti u proteklom razdoblju obuhvaćenom statistikom pogonskih događaja umanjenoj za trajne prisilne i planirane zastoje s unutarnjim razlogom.

$OC_{i,\mathrm{kl}}(j)$: godišnji operativni troškovi rada sustava uzrokovani slabostima u mreži u i-toj godini za j-ti analizirani scenarij uz potpunu neraspoloživost voda ili transformatora k.

— the average unavailability of all lines and transformers (including those older than 40 years), based on the statistics of operation events,
— reduced unavailability of lines and transformers older than 40 years after performed revitalization, where the unavailability of particular candidates is defined under the assumption of ideal reduction to zero permanent forced and planned outages caused by internal reason,
— permanent unavailability of a line or transformer (unavailability 100 %),
— full availability of a line or transformer (unavailability 0 %).

The role of a line or transformer is assessed on the basis of differences in the system's operating costs caused by weaknesses in the network for particular tested availability levels of the observed lines and transformers. For an assessment of the role of individual lines and transformers the following variables are introduced:

$MC_{i,\mathrm{k}}(j)$: marginal gain from the increased capacity of a line or transformer k (decrease in the EPS's operating costs at an increase in the transmission capability of the line or the apparent power of transformer k by 1 MW) in the i-th year, for the j-th analyzed scenario, given the estimated unavailability of lines and transformers in the network.

$OC_i(j)$: the system's annual operating costs resulting from weaknesses in the network in the i-th year for the j-th analyzed scenario dependent on modeled uncertainties, given the estimated unavailability of lines and transformers in the network.

$OC_{i,\mathrm{k}}(j)$: the system's annual operating costs resulting from weaknesses in the network in the i-th year for the j-th analyzed scenario given the unavailability of the line or transformer k equal to the average value in the past period covered by the statistics of operation events.

$OC'_{i,\mathrm{k}}(j)$: the system's annual operating costs resulting from weaknesses in the network in the i-th year for the j-th analyzed scenario given the unavailability of the line or transformer k equal to the average value in the past period covered by the statistics of operation events, reduced by the permanent forced and planned outages for an internal reason.

$OC_{i,\mathrm{kl}}(j)$: the system's annual operating costs resulting from weaknesses in the network in the i-th year for the j-th analyzed scenario given total unavailability of the line or transformer k.

$OC_{i,k0}(j)$: godišnji operativni troškovi rada sustava uzrokovani slabostima u mreži u i-toj godini za j-ti analizirani scenarij uz potpunu raspoloživost voda ili transformatora k.

5.2 Kriteriji ovisni o stvarnom stanju jedinice

Stvarno stanje jedinica prijenosne mreže moguće je ocijeniti analizom i obradom različitih podataka vezanih za starost jedinice, pogonske uvjete kojima je bila izložena, povijest održavanja, vizualne inspekcije, dijagnostičke rezultate i dr. Cilj ocjenjivanja stvarnog stanja jedinica je prvenstveno određivanje kandidata za revitalizaciju, te određivanje visine ulaganja financijskih sredstava i aktivnosti koje je potrebno izvršiti nad promatranom jedinicom.

5.2.1 Starost jedinice

Starenje jedinica prijenosne mreže kontinuirani je proces tijekom kojega se narušava funkcionalnost istih. Za sve grupe istovrsnih jedinica prijenosne mreže (u ovom se radu promatra četiri grupe: 1) nadzemni vodovi, 2) kabelski vodovi, 3) kombinirani nadzemno-kabelski vodovi, 4) transformatori) definira se očekivana životna dob tih jedinica na temelju statističke analize podataka iz prošlosti (koji su ograničeni zbog relativno kratkog razdoblja funkcioniranja modernih izmjeničnih sustava električne energije).

Starost jedinice, u odnosu na očekivanu životnu dob grupe istovrsnih jedinica, određeni je pokazatelj njenog mogućeg stanja. Sve jedinice starije od očekivane životne dobi grupe istovrsnih jedinica potencijalni su kandidati za revitalizaciju, iako u konačnici možda neće biti nužno izvoditi bilo kakve aktivnosti na revitalizaciji ukoliko su ostali pokazatelji stanja promatrane jedinice povoljni. Prema tome, kandidat za revitalizaciju svaka je jedinica prijenosne mreže za koju je zadovoljeno:

$OC_{i,k0}(j)$: : the system's annual operating costs resulting from weaknesses in the network in the i-th year for the j-th analyzed scenario given full availability of the line or transformer k.

5.2 Criteria dependent on the real condition of a unit

The real condition of transmission network units can be assessed by analyzing and processing various data relating to the age of a unit, the operation conditions to which it was exposed, the history of maintenance, visual inspections, diagnostic results, etc. The purpose of assessing the real condition of the units is first of all to get a list of revitalization candidates and to appraise the amount of required finances, as well as activities to be carried out on the observed unit.

5.2.1 The age of a unit

The aging of transmission network units is an ongoing process in the course of which their functionality is being impaired. For all the groups comprising transmission network units of the same type (in the present work four groups are examined: 1) overhead lines, 2) cables, 3) combined overhead-cable lines, 4) transformers) life expectancy of these units is defined based on a statistical analysis of these past data (which are limited due to a relatively short operation period of modern AC power systems).

The age of a unit in relation to the life expectancy of a group of units of the same type is an indicator of its likely condition. All the units older than the life expectancy of the group of units of the same type are potential revitalization candidates, although eventually it may not be necessary to undertake any revitalization if the other indicators of the condition of the observed unit are favorable. Therefore, a revitalization candidate is any of the transmission network units for which the following requirement is met:

$$T_k \geq T \ , \tag{28}$$

gdje je T_k starost promatrane jedinice k, a T očekivana životna dob grupe istovrsnih jedinica prijenosne mreže (radi pojednostavljenja može se uzeti $T = 40$ godina za promatrane grupe jedinica, tj. za vodove i transformatore).

5.2.2 Neraspoloživost jedinice

Za starije jedinice prijenosne mreže očekuje se porast njihove neraspoloživosti. Kao kandidate za revitalizaciju potrebno je izdvojiti sve jedinice čija

where T_k is the age of the observed unit k, and T is the life expectancy of the group of transmission network units of the same type (for the sake of simplicity we can take $T = 40$ years for the observed groups of units, i.e., lines and transformers).

5.2.2 Unavailability of units

For older transmission network units an increase in their unavailability is expected. As revitalization candidates all those units should be singled out je prosječna neraspoloživost u proteklom petogodišnjem razdoblju obuhvaćenom statistikom pogonskih događaja veća od prosječne neraspoloživosti u istom razdoblju cjelokupne grupe istovrsnih jedinica, odnosno one jedinice kod kojih je:

$$\begin{aligned} \bar{q}_{\mathrm{k}} &\geq \bar{q}_{\mathrm{NV}} \\ \bar{q}_{\mathrm{k}} &\geq \bar{q}_{\mathrm{K}} \\ \bar{q}_{\mathrm{k}} &\geq \bar{q}_{\mathrm{NK}} \\ \bar{q}_{\mathrm{k}} &\geq \bar{q}_{\mathrm{T}} \end{aligned} , \qquad (29)$$

gdje su:

- $\bar{q}_{\mathrm{k}}$ – prosječna neraspoloživost promatrane jedinice k u zadnjem petogodišnjem razdoblju,
- $\bar{q}_{\mathrm{NV}}$ – prosječna neraspoloživost svih nadzemnih vodova u promatranoj mreži u zadnjem petogodišnjem razdoblju,
- $\bar{q}_{\mathrm{K}}$ – prosječna neraspoloživost svih kabelskih vodova u promatranoj mreži u zadnjem petogodišnjem razdoblju,
- $\bar{q}_{\mathrm{NK}}$ – prosječna neraspoloživost svih kombiniranih nadzemno-kabelskih vodova u promatranoj mreži u zadnjem petogodišnjem razdoblju,
- $\bar{q}_{\mathrm{T}}$ – prosječna neraspoloživost svih transformatora u promatranoj mreži u zadnjem petogodišnjem razdoblju.

5.2.3 Rezultati pregleda i dijagnostike jedinice

Stanje promatrane jedinice prijenosne mreže moguće je ocijeniti vizualnim pregledom ili podvrgavanjem određenim dijagnostičkim postupcima. Kompanija u čijem su vlasništvu jedinice prijenosne mreže, odnosno posebni odjeli zaduženi za upravljanje imovinom, redovito provodi vizualnu inspekciju opreme, a po potrebi podvrgavaju određenu opremu i dijagnostičkim ispitivanjima. Kao kandidati za revitalizaciju uvrštavaju se sve one jedinice čiji vizualni pregledi ili rezultati dijagnostike ukazuju na njihovu smanjenu funkcionalnost i općenito ugroženost.

5.2.4 Troškovi održavanja jedinice

Svaka jedinica tijekom svog životnog vijeka redovito se održava kako bi se očuvala njena funkcionalnost. U održavanje se ulažu određena financijska sredstva koja su na razini pojedinih vremenskih razdoblja približno konstantna. Starije jedinice mreže generalno zahtijevaju veća financijska sredstva potrebna za održavanje. Broj unutarnjih kvarova sve je veći pa raste i potreba za aktivnostima na njihovom otklanjanju. Istodobno raste i potreba preventivnog održavanja, odnosno planiranih zastoja, kako bi se otklanjali pojedini nedostaci i omogućilo normalno funkcioniranje jedinice. Kao kandidati za revitalizaciju izdvojene

the average unavailability of which over the past five-year period covered by the operation statistics exceeds the average unavailability in the same period of the whole group of units of the same type, or those units with which:

where:

- $\bar{q}_{\mathrm{k}}$ – average unavailability of the observed unit k in the last five-year period,
- $\bar{q}_{\mathrm{NV}}$ – average unavailability of all overhead lines in the observed network in the last five-year period,
- $\bar{q}_{\mathrm{K}}$ – average unavailability of all cables in the observed network in the last five-year period,
- $\bar{q}_{\mathrm{NK}}$ – average unavailability of all combined overhead-cable lines in the observed network in the last five-year period,
- $\bar{q}_{\mathrm{T}}$ – average unavailability of all transformers in the observed network in the last five-year period.

5.2.3 Inspection and diagnostic results

The state of an observed transmission network unit can be assessed through visual inspection or by subjecting it to certain diagnostic procedures. The company which owns the transmission network units, i.e., its specialized departments in charge of assets management, conducts regular visual inspections of the equipment and, as required, subject certain equipment to diagnostic tests. As revitalization candidates qualify all those units the visual inspections of which or diagnostic results suggest diminished functionality or, generally, vulnerability.

5.2.4 Maintenance costs

Each unit is regularly maintained throughout its lifetime in order to preserve its functionality. Certain funds are spent on maintenance which are approximately constant at the level of particular periods of time. Older network units generally require more maintenance funds. Internal failures are steadily rising in number, and so is a need for activities aimed to correct them. At the same time, a need is rising for preventive maintenance, and thereby for planned outages, so as to eliminate certain irregularities and enable the unit concerned to function normally. Singled out as revitalization su one jedinice čiji su troškovi održavanja, promatrano u određenom vremenskom razdoblju (na primjer u godini dana), znatno veći od troškova preventivnog održavanja, odnosno troškova održavanja istovrsnih novijih jedinica mreže. Prema tome, kandidat za zamjene i rekonstrukcije svaka je jedinica prijenosne mreže za koju je zadovoljeno:

candidates are those units the maintenance costs of which, viewed over a certain period of time (e.g., a year's time), by far exceed the preventive maintenance costs, or the maintenance costs of new network units of the same type. Therefore, a candidate for revitalization is any of the transmission network units for which the following requirement is met:

$$C_{\mathrm{m}}(\mathrm{k}) >> C_{\mathrm{pm}}(\mathrm{k}) \,, \tag{30}$$

gdje su:

$C_{\mathrm{m}}(\mathrm{k})$ – aktualni godišnji troškovi održavanja promatrane jedinice k, a

$C_{\mathrm{pm}}(\mathrm{k})$ – godišnji troškovi preventivnog održavanja novije jedinice istovjetne jedinici k.

where:

$C_{\mathrm{m}}(\mathrm{k})$ – annual actual maintenance costs of the observed unit k, and

$C_{\mathrm{pm}}(\mathrm{k})$ – annual preventive maintenance costs of a new unit identical to unit k.

5.2.5 Tehničko stanje jedinica i ostali pokazatelji stanja

Pod kriterijima za ocjenu tehničkog stanja jedinica prijenosne mreže svrstavaju se: tehnička neispravnost jedinice ili komponente, tehnička greška jedinice ili komponente mreže takva da je ekonomski neisplativo tu grešku otkloniti, nezadovoljavajuće karakteristike jedinice ili komponente mreže s obzirom na očekivane pogonske uvjete u planskom razdoblju (opterećenja, kratki spoj), nezadovoljavanje postojećih i budućih tehničkih propisa koje jedinica mreže mora zadovoljavati. Pod tehnički neispravnom jedinicom ili komponentom mreže podrazumijeva se ona jedinica ili komponenta mreže koja je trajno u stanju zastoja radi kvara, te ona jedinica ili komponenta mreže koja je u pogonu, ali predstavlja opasnost ili rizik za ljude ili imovinu i ispravno funkcioniranje ostalih jedinica i komponenti mreže. Pod tehničkom greškom jedinice ili komponente prijenosne mreže podrazumijeva se posljedica događaja koji promatranu jedinicu postavlja u stanje privremene ili trajne neispravnosti. Kao kandidate za revitalizaciju izdvajaju se sve jedinice koje ne zadovoljavaju neki od nabrojenih tehničkih kriterija. Osim navedenog, na stanje jedinica prijenosne mreže i potrebe revitalizacije značajan utjecaj mogu imati i određene okolnosti izvan promatranih jedinica, kao što su nedostatak osoblja obučenog za održavanje pojedinih tipova komponenata mreže, nedostatak rezervnih dijelova nužnih za normalan pogon jedinice ili komponente mreže, nezadovoljenje različitih propisa vezanih za zaštitu okoliša, nezadovoljenje različitih zahtjeva regulatorne agencije, te ugroženost osoblja zaduženog za održavanje i okolne opreme.

5.2.5 Technical condition of units and other status indices

Classified under the criteria for an assessment of the technical condition of the transmission network units are: the technical faultiness of a unit or component, the technical error of a network unit or component, such as making the rectification of the error commercially unfeasible, unsatisfactory characteristics of a network unit or component in respect of the expected operation conditions in the planning period (loads, short-circuits), non-compliance with the existing and future technical regulations that a network unit must comply with. By a technically faulty network unit or component is meant one which is permanently in a state of outage caused by a failure, as well as one which is in operation but poses a risk to persons and property and to the proper functioning of other network units and components. By a technical error of a transmission network unit or component is meant the consequence of an event that places the observed unit in a state of temporary or permanent faultiness. Singled out as revitalization candidates are those units which do not meet one of the specified technical criteria. Apart from the aforementioned, the state of the transmission network units and the need for revitalization can also be significantly influenced by some circumstances outside the observed units, such as the shortage of staff trained for the maintenance of specific types of the network components, the shortage of spare parts needed for normal operation of a network unit or component, non-compliance with various regulations relating to environmental protection, non-compliance with various regulations passed by the regulatory agency, risk exposure of personnel doing maintenance on nearby equipment.

5.3 Kriteriji ovisni o ulozi i važnosti jedinice unutar EES-a

5.3.1 Kriterij povećanja očekivanih operativnih troškova rada elektroenergetskog sustava (starosni kriterij)
Unutar razmatranog kriterija izračunavaju se očekivani godišnji operativni troškovi rada elektroenergetskog sustava pri procijenjenoj neraspoloživosti voda ili transformatora k kandidata za revitalizaciju ($OC_i\ (j)$), za sve analizirane vremenske presjeke i i scenarije pogona j, te očekivani godišnji operativni troškovi rada elektroenergetskog sustava pri prosječnoj neraspoloživosti promatranog voda ili transformatora k u razdoblju obuhvaćenom statistikom pogonskih događaja ($OC_{i,k}\ (j)$). Za sve promatrane vremenske presjeke i, i scenarije pogona j, izračunavaju se prosječne vrijednosti te razlike:

5.3 Criteria dependent on the role and importance of a unit within the EPS

5.3.1 Criterion of an increase in the EPS's expected operating costs (age criterion)
Calculated within the reviewed criterion are the EPS's expected annual operating costs at the estimated unavailability of a line or a transformer k, the revitalization candidates ($OC_i\ (j)$), for all analyzed time cross-sections i and operation scenarios j, and the EPS's expected annual operating costs at the average unavailability of an observed line or transformer k in the period covered by the statistics of operation events ($OC_{i,k}\ (j)$). For all the observed time cross-sections i, and operation scenarios j the average values of that difference are calculated:

$$\overline{OC_i(j) - OC_{i,\mathrm{k}}(j)} = \frac{\sum_{i=1}^{N_i}\sum_{j=1}^{N_j}\left[OC_i(j) - OC_{i,\mathrm{k}}(j)\right] p_j}{N_i} \tag{31}$$

gdje je:

- P_j – vjerojatnost nastanka scenarija j unutar promatrane godine i,
- N_i – ukupni broj godina unutar promatranog vremenskog razdoblja,
- N_j – ukupni broj scenarija.

Parcijalna lista prioriteta za revitalizaciju s obzirom na promatrani kriterij određuje se na temelju maksimalne prosječne razlike između očekivanih godišnjih operativnih troškova rada sustava pri procijenjenoj neraspoloživosti voda ili transformatora k, kandidata za revitalizaciju, te očekivanih godišnjih operativnih troškova rada elektroenergetskog sustava pri prosječnoj neraspoloživosti promatranog voda ili transformatora k u razdoblju obuhvaćenom statistikom pogonskih događaja:

where:

- P_j – probability of the occurrence of scenario j within the observed year i,
- N_i – total number of years within the observed period of time,
- N_j – total number of scenarios.

A partial priority list for revitalization in respect of the observed criterion is compiled on the basis of a maximum average difference between the system's expected annual operating costs at the estimated unavailability of a line or transformer k, the revitalization candidates, and the EPS's expected annual operating costs at the average unavailability of the observed line or transformer k in the period covered by the statistics of operation events:

$$\mathrm{Max}\left\{\overline{OC_i(j) - OC_{i,\mathrm{k}}(j)}\right\}. \tag{32}$$

Prema tome, za sve analizirane vremenske presjeke i, te scenarije pogona j, traži se maksimalna prosječna razlika između povećanja operativnih troškova rada sustava uzrokovanih slabostima u mreži pri procijenjenoj neraspoloživosti vodova ili transformatora i povećanja operativnih troškova rada sustava pri raspoloživosti pojedinačnih vodova ili transformatora određenoj na temelju prosjeka u razdoblju obuhvaćenom statistikom pogonskih

Therefore, for all the analyzed time cross-sections i and operation scenarios j a maximum average difference is sought between the increase in the system's operating costs caused by weaknesses in the network at the estimated unavailability of lines or transformers and the increase in the system's operating costs at the availability of individual lines or transformers defined on the basis of the average in the period covered by the događaja. Vod ili transformator s najvećom razlikom između te dvije veličine najvažniji je kandidat za revitalizaciju u promatranoj kategoriji.

Za razmatranje ovog kriterija osnovna je pretpostavka da će se za vodove i transformatore starije od 40 godina neraspoloživost povećavati u svakoj promatranoj godini u kratkoročnom razdoblju, što će rezultirati povećanjem troškova rada EES-a za pojedine vodove i transformatore. Razlika između tako određenih troškova rada sustava i troškova rada sustava ukoliko bi se neraspoloživosti pojedinačnih vodova ili transformatora održavale na postignutom prosjeku u proteklom razdoblju, ujedno prikazuje i djelomičnu procjenu ekonomske opravdanosti ulaganja u održavanje ili revitalizaciju pojedinih vodova i transformatora,kojim bi se izbjeglo povećanje njihove neraspoloživosti.

5.3.2 Kriterij smanjenja očekivanih operativnih troškova rada EES-a nakon revitalizacije (ekonomski kriterij)

Unutar razmatranog kriterija promatra se najveća prosječna razlika očekivanih godišnjih operativnih troškova rada elektroenergetskog sustava pri procijenjenoj neraspoloživosti pojedinačnih vodova i transformatora k, kandidata za revitalizaciju ($OC_{i,\,\mathrm{kl}}\,(j)$), te neraspoloživosti tih vodova jednakoj prosječnoj vrijednosti u proteklom razdoblju obuhvaćenom statistikom pogonskih događaja umanjenoj za trajne prisilne i planirane zastoje s unutarnjim razlogom ($OC_i\,(j)$). Za sve promatrane vremenske presjeke i, i scenarije pogona j, izračunavaju se prosječne vrijednosti te razlike:

statistics of operation events. The line or transformer with the greatest difference between these two values is the most important revitalization candidate in the observed category.

In examining this criterion the basic assumption is that for the lines and transformers older than 40 years unavailability will rise in every observed year in a short-term period, which will result in higher operating costs of the EPS for particular lines and transformers. The difference between the thus determined operating costs of the system and the operating costs of the system if the unavailabilities of individual lines or transformers were kept at the average rate attained in the previous period also partially illustrates the economic justification of investment in the maintenance or revitalization of some lines and transformers with a view to avoiding an increase in their unavailability.

5.3.2 Criterion of reduction in the expected operating costs of the EPS after revitalization (economic criterion)

Within the examined criterion the greatest average difference is observed between the expected annual operating costs of the EPS at the estimated unavailability of particular lines and transformers k, the revitalization candidates ($OC_{i,\,\mathrm{kl}}\,(j)$), and the unavailability of these lines equal to the average value in the previous period covered by the statistics of operation events reduced by permanent forced and planned outages occurred for an internal reason ($OC_i\,(j)$). For all the observed time cross-sections i and operation scenarios j the average values of that difference are calculated:

$$\overline{OC_i(j) - OC'_{i,\mathrm{k}}(j)} = \frac{\sum_{i=1}^{N_i}\sum_{j=1}^{N_j}\left[OC_i(j) - OC'_{i,\mathrm{k}}(j)\right]\cdot p_j}{N_i} \quad . \tag{33}$$

Parcijalna lista prioriteta s obzirom na promatrani kriterij određuje se na temelju maksimalne prosječne razlike između očekivanih godišnjih operativnih troškova rada sustava za promatrane razine neraspoloživosti kandidata za revitalizaciju k:

The partial priority list against the observed criterion is defined on the basis of a maximum average difference between the expected annual operating costs of the system for the observed unavailability levels of the revitalization candidates k:

$$\mathrm{Max}\left\{\overline{OC_i(j) - OC'_{i,\mathrm{k}}(j)}\right\} \quad . \tag{34}$$

Pretpostavka je da će se za vodove i transformatore starije od 40 godina neraspoloživost povećavati u svakoj promatranoj godini u kratkoročnom razdoblju, što će rezultirati u povećanju troškova rada EES-a. Razlika između tako određenih troš-

It is assumed that for lines and transformers older than 40 years unavailability will rise in every observed year in a short-term period, which will result in increased operating costs of the EPS. The difference between the thus determined operating kova rada sustava i troškova rada sustava ukoliko bi svaki pojedinačni vod i transformator imao manju neraspoloživost kao rezultat određenih aktivnosti na revitalizaciji, prikazuje procjenu ekonomske opravdanosti ulaganja u revitalizaciju pojedinih vodova i transformatora kojim bi se povećala njihova raspoloživost, u idealnom slučaju do vrijednosti određene samo pod utjecajem zastoja s vanjskim razlozima, te privremenih i prolaznih prisilnih zastoja s unutarnjim razlogom. U stvarnim okolnostima neće se moći postići nulta neraspoloživost radi trajnih prisilnih i planiranih zastoja s unutarnjim razlogom niti jednog voda i transformatora na kojem su provedene aktivnosti na revitalizaciji, pa promatramo idealnu ekonomsku dobit od revitalizacije.

5.3.3 Kriterij opasnosti od trajnog otkaza

Za razmatrani kriterij promatra se najveća razlika između prosječnih očekivanih godišnjih operativnih troškova rada EES-a pri trajnoj neraspoloživosti ($OC_{i,\mathrm{kl}}(j)$) i procijenjenoj neraspoloživosti pojedinačnih vodova i transformatora k ($OC_i(j)$), kandidata za revitalizaciju. Izračunavaju se očekivani godišnji operativni troškovi rada sustava uzrokovani slabostima u mreži pri trajno isključenoj pojedinačnoj grani (vodu ili transformatoru) tijekom čitavog promatranog razdoblja za sve analizirane scenarije pogona, te se nadalje izračunava razlika između tako određenih troškova i troškova u baznom stanju definiranim procijenjenom neraspoloživosti vodova i transformatora. Na temelju razmatranog kriterija, a ovisno o stvarnom stanju vodova, može se definirati operativna lista prioriteta za revitalizaciju vodova s ciljem izbjegavanja porasta troškova rada sustava kod trajne obustave pogona nekog voda (npr. radi lošeg stanja stupova, pucanja vodiča, ugrožavanja sigurnosnih propisa i sl.) ili transformatora (npr. radi curenja ulja, korozije kotla i dr.). Za sve promatrane vremenske presjeke i, i scenarije pogona j, izračunavaju se prosječne vrijednosti razlike očekivanih operativnih troškova rada sustava pri trajnoj neraspoloživosti i procijenjenoj neraspoloživosti kandidata:

5.3.3 Criterion of a risk of permanent failure

Examined for the criterion in question is the greatest difference between the average expected annual operating costs of the EPS at a permanent unavailability ($OC_{i,\mathrm{kl}}(j)$) and the estimated unavailability of particular lines and transformers k ($OC_i(j)$), the revitalization candidates. The expected annual operating costs of the system caused by weaknesses in the network at a permanently switched-off particular branch (line or transformer) throughout the observed period for all the analyzed operation scenarios are calculated. Further calculated is the difference between the thus defined costs and the base state costs defined by the estimated unavailability of lines and transformers. Based on the examined criterion and depending on the real condition of the lines, it is possible to define the operating priority list for the revitalization of the lines with a view to avoiding an increase in the operating costs of the system in the event of permanently discontinued operation of a line (e.g., due to poor condition of the towers, wire breakage, infringement of safety regulations and the like) or a transformer (e.g., due to oil leakage, boiler corrosion, etc.). For all the observed time cross-sections i and operation scenarios j the average differences are calculated between the expected operating costs of the system at permanent unavailability and the estimated unavailability of candidates:

$$\overline{OC_{i,\mathrm{k}1}(j)-OC_i(j)}=\frac{\sum_{i=1}^{N_i}\sum_{j=1}^{N_j}\left[OC_{i,\mathrm{k}1}(j)-OC_i(j)\right]\cdot p_j}{N_i} \qquad (35)$$

Parcijalna lista prioriteta prema razmatranom kriteriju određuje se na temelju maksimalne prosječne razlike između očekivanih godišnjih operativnih troškova rada sustava za promatrane razine neraspoloživosti kandidata k:

The partial priority list against the observed criterion is defined on the basis of a maximum average difference between the expected annual operating costs of the system for the observed unavailability levels of the candidates k:

$$\text{Max}\left\{\overline{OC_{i,\mathrm{k}1}(j)-OC_i(j)}\right\} \quad (36)$$

Za sve analizirane vremenske presjeke i, i scenarije pogona j, traži se maksimalna razlika između povećanja operativnih troškova rada sustava pri trajnoj neraspoloživosti pojedinog voda ili transformatora i povećanja operativnih troškova rada sustava pri procijenjenoj neraspoloživosti vodova i transformatora. Vod ili transformator s najvećom razlikom između te dvije veličine najvažniji je kandidat za revitalizaciju u promatranoj kategoriji.

For all the analyzed time cross-sections i and operation scenarios j a maximum average difference is sought between the increase in the system's operating costs at permanent unavailability of a line or a transformer and the increase in the system's operating costs at the availability of the lines and transformers. The line or transformer with the greatest difference between these two values is the most important revitalization candidate in the observed category.

5.3.4 Kriterij važnosti jedinice u EES-u

Unutar razmatranog kriterija izračunavaju se očekivani godišnji operativni troškovi rada EES-a pri trajnoj neraspoloživosti voda ili transformatora k, kandidata za revitalizaciju ($OC_{i,\,\mathrm{k}1}\,(j)$), za sve analizirane vremenske presjeke i i scenarije pogona j, te očekivani godišnji operativni troškovi rada EES-a pri punoj raspoloživosti promatranog voda ili transformatora k ($OC_{i,\,\mathrm{k}0}\,(j)$). Za sve promatrane vremenske presjeke i, i scenarije pogona j, izračunavaju se prosječne vrijednosti te razlike:

5.3.4 Criterion of the importance of a unit in the EPS

Calculated within the criterion in question are the expected annual operating costs of the EPS at permanent unavailability of a line or transformer k, the revitalization candidates ($OC_{i,\,\mathrm{k}1}\,(j)$), for all the analyzed time cross-sections i and operation scenarios j and the expected annual operating costs of the EPS at full availability of the observed line or transformer k ($OC_{i,\,\mathrm{k}0}\,(j)$). For all the reviewed time cross-sections i and operation scenarios j the average values of that difference are calculated:

$$\overline{OC_{i,\mathrm{k}1}(j)-OC_{i,\mathrm{k}0}(j)} = \frac{\sum_{i=1}^{N_i}\sum_{j=1}^{N_j}\left[OC_{i,\mathrm{k}1}(j)-OC_{i,\mathrm{k}0}(j)\right]p_j}{N_i} \quad (37)$$

Parcijalna lista prioriteta s obzirom na promatrani kriterij određuje se na temelju maksimalne prosječne razlike između očekivanih godišnjih operativnih troškova rada sustava pri trajnoj neraspoloživosti voda ili transformatora k, kandidata za revitalizaciju, te očekivanih godišnjih operativnih troškova rada EES-a pri punoj raspoloživosti promatranog voda ili transformatora k:

The partial priority list against the observed criterion is defined on the basis of a maximum average difference between the expected annual operating costs of the system at permanent unavailability of a line or transformer k, the revitalization candidates, and the expected annual operating costs of the EPS at full availability of the observed line or transformer k:

$$\text{Max}\left\{\overline{OC_{i,\mathrm{k}1}(j)-OC_{i,\mathrm{k}0}(j)}\right\}. \quad (38)$$

Vod ili transformator s najvećom razlikom između te dvije veličine najvažniji je kandidat za revitalizaciju u promatranoj kategoriji. Razlika između prosječnih očekivanih godišnjih operativnih troškova rada sustava pri trajnoj neraspoloživosti i punoj raspoloživosti kandidata ukazuje na važnost tog kandidata u EES-u. Kandidat s maksimalnom razlikom promatranih troškova najznačajnija je grana unutar sustava.

The line or transformer with the greatest difference between these two values is the most important revitalization candidate in the observed category. The difference between the average expected annual operating costs of the system at permanent unavailability and full availability of a candidate points to the importance of that candidate in the EPS. The candidate with a maximum difference of observed costs is the most important branch within the system.

5.3.5 Kriterij maksimalne marginalne dobiti
Unutar razmatranog kriterija promatra se najveća marginalna dobit neke grane (voda ili transformatora) za sve analizirane vremenske presjeke i i scenarije pogona j. Na taj način definiramo listu prioriteta onih vodova i transformatora kojima kroz revitalizaciju eventualno treba povećati prijenosnu moć ili prividnu snagu, ugradnjom vodiča većeg presjeka, vodiča s većim dozvoljenim termičkim opterećenjem ili zamjenom transformatora jedinicom veće prividne snage. Prije donošenja odluke o takvoj zamjeni vodiča ili transformatora potrebno je detaljno sagledati ekonomsku dobit koja iz te zamjene slijedi.

Za sve promatrane vremenske presjeke i, i scenarije pogona j, izračunavaju se prosječne marginalne dobiti grana:

5.3.5 Criterion of maximum marginal gain
Reviewed within the criterion in question is the highest marginal gain of a branch (line or transformer) for all the analyzed time cross-sections i and operation scenarios j. In this way we define the priority list of those lines and transformers transmission capacity or rated power of which may have to be enhanced through revitalization by installing a larger- cross-section conductor, a conductor with a higher permissible thermal load, or by replacing the transformer with a unit of higher apparent power. Before deciding on such a replacement of the conductor or transformer it is necessary to consider in detail the economic gains that the replacement may bring.

For all the reviewed time cross-sections i and operation scenarios j the average marginal gains of the branches are calculated:

$$\overline{MC_{i,\mathrm{k}}(j)} = \frac{\sum_{i=1}^{N_i}\sum_{j=1}^{N_j}\left[MC_{i,\mathrm{k}}(j)\right]\cdot p_j}{N_i} , \qquad (39)$$

gdje su:

- $MC_{i,\mathrm{k}}(j)$ – marginalne dobiti grane k u godini i i scenariju pogona j,
- P_j – vjerojatnost nastanka scenarija j unutar promatrane godine i, a
- N_i – broj godina unutar promatranog vremenskog razdoblja.

where:

- $MC_{i,\mathrm{k}}(j)$ – marginal gains of branch k in year i and operation scenario j,
- P_j – probability of the occurrence of scenario j within the observed year i, and
- N_i – number of years within the observed period of time.

Lista prioriteta prema razmatranom kriteriju određuje se na temelju maksimalne prosječne marginalne dobiti:

The priority list against the criterion in question is defined on the basis of maximum average marginal gain:

$$\mathrm{Max}\left\{\overline{MC_{i,\mathrm{k}}(j)}\right\} . \qquad (40)$$

Za sve analizirane vremenske presjeke i scenarije pogona traži se maksimalna marginalna dobit pojedinog voda ili transformatora. Vod ili transformator s najvećom marginalnom dobiti najvažniji je kandidat za revitalizaciju u promatranoj kategoriji.

For all the analyzed time cross-sections and operation scenarios the maximum marginal gain of a line or transformer is sought. The line or transformer with the highest marginal gain is the most important revitalization candidate in the observed category.

6 METODOLOGIJA IZRADE LISTE PRIORITETA ZA REVITALIZACIJU

Budući da su u prethodnom poglavlju definirani pojedinačni kriteriji za revitalizaciju potrebno je

6 METHODOLOGY OF COMPILING A PRIORITY LIST FOR REVITALIZATION

In the preceding section the particular revitalization criteria are defined, so it is necessary to comujediniti sve kriterije te izraditi zajedničku listu prioriteta. Radi toga su definirane dvije veličine: indeks stanja kandidata, te indeks važnosti u EES-u kandidata za revitalizaciju.

Obje veličine izračunavaju se uključivanjem odgovarajućih kriterija u jedinstvenu funkciju pri čemu se važnost pojedinih kriterija definira odgovarajućim težinskim faktorima (oznaka w). Težinski faktori se određuju subjektivno, na temelju procjene operatora prijenosnog sustava i važnosti koju on daje pojedinim kriterijima. Ovisnost liste prioriteta za revitalizaciju o težinskim faktorima moguće je naknadno ispitivati analizom osjetljivosti, varirajući ih u određenom rasponu.

6.1 Indeks stanja kandidata za revitalizaciju

Indeks stanja kandidata za revitalizaciju (oznaka $ZiR_{\mathrm{k\_st}}$) izračunava se na temelju promatranih kriterija ovisnih o stvarnom stanju promatrane jedinice, na način da su za pojedine kriterije (starost, neraspoloživost, troškovi održavanja) promatrane veličine normalizirane (izražene kao omjer između promatrane veličine za neki kandidat i najveće promatrane veličine u toj kategoriji uzimajući u obzir sve kandidate), a zatim pomnožene s određenim težinskim faktorima te zbrojene. Za pojedine kriterije nisu kvantificirane veličine kojima bi ih jednoznačno mogli definirati (rezultati pregleda i dijagnostike jedinice, tehničko stanje jedinica i ostali pokazatelji), pa se postupa na način da operator prijenosnog sustava subjektivno pridružuje vrijednosti između 0 i 1 promatranim kriterijima, pri čemu se vrijednost 1 pridružuje onim kandidatima kod kojih je stanje utvrđeno vizualnim pregledom ili dijagnostikom potpuno nezadovoljavajuće, ili tehničko stanje ili ostali pokazatelji stanja potpuno su nezadovoljavajući, dok se vrijednost 0 pridružuje onim kandidatima kod kojih je stanje utvrđeno vizualnim pregledom ili dijagnostikom potpuno zadovoljavajuće, i tehničko stanje ili ostali pokazatelji stanja su potpuno zadovoljavajući. Matematički indeks stanja kandidata k za revitalizaciju formulira se na sljedeći način:

bine all the criteria and compile a common priority list. For that reason two values are defined: the condition index of candidates and the index of the EPS significance of revitalization candidates.

Both values are calculated by including appropriate criteria in a single function, where the importance of individual criteria is defined by related weighting factors (sign w). The weighting factors are defined subjectively, by personal judgment of the transmission system operator and based on the importance the operator attaches to particular criteria. The dependence of the revitalization priority list on the weighting factors can be subsequently examined by a sensitivity analysis, varying them within a certain range.

6.1 Condition index of revitalization candidates

The condition index of revitalization candidates (denoted $ZiR_{\mathrm{k\_st}}$) is computed on the basis of the observed criteria dependent on the real condition of the observed unit, in such a way that for particular criteria (age, unavailability, maintenance costs) the observed values are normalized (expressed as a ratio between the observed value for a candidate and the greatest observed value in that category, with all the candidates taken into consideration) and then multiplied with appropriate weighting factors and summed up. For certain criteria values are not quantified by which they could be clearly defined (inspection and diagnostic results, the technical condition of units and other indicators), so the transmission system operator subjectively assigns values between 0 and 1 to the observed criteria, with value 1 being assigned to those candidates where by visual inspection or diagnostics the status has been found as entirely unsatisfactory, or the technical status or other status indices are entirely unsatisfactory, and value 0 being assigned to those candidates where by visual inspection or diagnostics the status has been found as entirely satisfactory, and the technical status or other status indices have been found as entirely satisfactory as well. The mathematical condition index of revitalization candidates k is formulated as follows:

$$ZiR_{\mathrm{k\_st}} = w_{\mathrm{s1}} \cdot \frac{\dfrac{T_{\mathrm{k}}}{T}}{Max\left\{\dfrac{T_{\mathrm{k}}}{T}\right\}} + w_{\mathrm{s2}} \cdot \frac{\dfrac{q_{\mathrm{k}}}{q_J}}{Max\left\{\dfrac{q_{\mathrm{k}}}{q_J}\right\}} + w_{\mathrm{s3}} \cdot \frac{\dfrac{C_m(\mathrm{k})}{C_{pm}(k)}}{Max\left\{\dfrac{C_m(\mathrm{k})}{C_{pm}(\mathrm{k})}\right\}} + w_{\mathrm{s4}} \cdot VID + w_{\mathrm{s5}} \cdot TS, \qquad (41)$$

pri čemu je:

$ZiR_{\mathrm{k\_st}}$ – indeks stanja kandidata za revitalizaciju k,
w_{s1} – težinski faktor pridružen kriteriju starosti kandidata ($0 \leq w_{\mathrm{s1}} \geq 0{,}2$),

where:

$ZiR_{\mathrm{k\_st}}$ – condition index of revitalization candidates k,
w_{s1} – weighting factor assigned to the criterion of

w_{s2} – težinski faktor pridružen kriteriju neraspoloživosti kandidata ($0 \le w_{s2} \ge 0{,}2$),
w_{s3} – težinski faktor pridružen kriteriju troškova održavanja kandidata ($0 \le w_{s3} \ge 0{,}2$),
w_{s4} – težinski faktor pridružen kriteriju rezultata vizualne inspekcije i dijagnostičkih pregleda ($0 \le w_{s4} \ge 0{,}2$),
w_{s5} – težinski faktor pridružen kriteriju tehničkog stanja i ostalih pokazatelja stanja ($0 \le w_{s5} \ge 0{,}2$),
VID – subjektivno određena ocjena vizualne inspekcije i dijagnostičkih pregleda ($0 \le VID \ge 1$),
TS – subjektivnoodređenaocjenatehničkogstanja i ostalih pokazatelja stanja ($0 \le TS \ge 1$).

Svi razlomci u gornjem izrazu poprimaju vrijednosti između 0 i 1, kao i subjektivno određene veličine *VID* i *TS*, a da bi se omogućila usporedba i jednako tretiranje indeksa stanja i indeksa važnosti u EES-u kandidata za revitalizaciju, svi pojedinačni težinski faktori moraju biti određeni u rasponu od 0 do 0,2. Uz tako određene težinske faktore maksimalan mogući indeks stanja iznosi 1.

6.2 Indeks važnosti u EES-u kandidata za revitalizaciju

Indeks važnosti u EES-u kandidata za revitalizaciju (oznaka ZiR_{k_zn}) izračunava se na temelju pet promatranih kriterija ovisnih o ulozi i važnosti jedinice unutar sustava, na način da su razlike troškova za pojedine kriterije normalizirane (izražene kao omjer između razlike troškova pojedinog kandidata i maksimalne razlike troškova u promatranoj kategoriji za sve kandidate), a zatim pomnožene s određenim težinskim faktorima te zbrojene. Kandidati su poredani prema padajućim vrijednostima tako zbrojenih veličina. Matematički se to može izraziti na sljedeći način:

the candidate's age ($0 \le w_{s1} \ge 0{,}2$),
w_{s2} – weighting factor assigned to the criterion of the candidate's unavailability ($0 \le w_{s2} \ge 0{,}2$),
w_{s3} – weighting factor assigned to the criterion of the candidate's maintenance costs ($0 \le w_{s3} \ge 0{,}2$),
w_{s4} – weighting factor assigned to the criterion of the results of visual inspection and diagnostic examinations ($0 \le w_{s4} \ge 0{,}2$),
w_{s5} – weighting factor assigned to the criterion of the technical status and other status indices ($0 \le w_{s5} \ge 0{,}2$),
VID – subjective evaluation of visual inspection and diagnostic examinations ($0 \le VID \ge 1$),
TS – subjective evaluation of the technical status and other status indices ($0 \le TS \ge 1$).

All fractions in the above expression assume values between 0 and 1, and so do the subjectively assessed values *VID* and *TS*. In order to ensure the comparison and equal treatment of condition index and significance index of the revitalization candidates in the EPS, all individual weighting factors must be defined within a range of 0 to 0,2. With the weighting factors thus defined, the maximum possible condition index amounts to 1.

6.2 EPS significance index of the revitalization candidates

The EPS significance index of the revitalization candidates (denoted ZiR_{k_zn}) is computed on the basis of five observed criteria dependent on the role and importance of the observed unit, in such a way that for particular criteria the observed values are normalized (expressed as a ratio between the cost difference for a candidate and the maximum cost difference in the observed category for all candidates) and then multiplied with appropriate weighting factors and summed up. The candidates are arranged in the descending order of the thus summed up values. Mathematically it can be expressed as follows:

$$ZiR_{k\_zn} = w_{z1} \cdot \frac{\overline{OC_i(j) - OC_{i,k}(j)}}{Max\{OC_i(j) - OC_{i,k}(j)\}} + w_{z2} \cdot \frac{\overline{OC_i(j) - OC'_{i,k}(j)}}{Max\{OC_i(j) - OC'_{i,k}(j)\}} + w_{z3} \cdot \frac{\overline{OC_{i,k1}(j) - OC_{i,k}(j)}}{Max\{OC_{i,k1}(j) - OC_{i,k}(j)\}} + w_{z4} \cdot \frac{\overline{OC_{i,k1}(j) - OC_{i,k0}(j)}}{Max\{OC_{i,k1}(j) - OC_{i,k0}(j)\}} + w_{z5} \cdot \frac{\overline{MC_{i,k}(j)}}{Max\{MC_{i,k}(j)\}} \quad (42)$$

pri čemu je:

ZiR_{k_zn} - indeks značaja u EES-u kandidata k,
w_{z1} - težinski faktor pridružen starosnom kriteriju $(0 \leq w_{z1} \geq 0{,}2)$,
w_{z2} - težinski faktor pridružen ekonomskom kriteriju $(0 \leq w_{z2} \geq 0{,}2)$,
w_{z3} - težinski faktor pridružen kriteriju opasnosti od trajnog otkaza $(0 \leq w_{z3} \geq 0{,}2)$,
w_{z4} - težinski faktor pridružen kriteriju važnosti u elektroenergetskom sustavu $(0 \leq w_{z4} \geq 0{,}2)$,
w_{z5} - težinski faktor pridružen kriteriju maksimalne marginalne dobiti $(0 \leq w_{z5} \geq 0{,}2)$.

Svi razlomci u gornjem izrazu poprimaju vrijednosti između 0 i 1, a da bi se omogućilo usporedbu i jednako tretiranje indeksa stanja i indeksa značaja u EES-u kandidata za revitalizaciju, svi pojedinačni težinski faktori moraju biti određeni u rasponu od 0 do 0,2. Uz tako određene težinske faktore maksimalan mogući indeks važnosti u EES-u iznosi 1.

Indeksi važnosti u EES-u kandidata za revitalizaciju ovisni su o iznosima neraspoloživosti svih grana u mreži, tako da promjena neraspoloživosti bilo koje grane dovodi do drugačijih rezultata i u konačnici utječe na listu prioriteta za revitalizaciju ostalih kandidata u mreži. Da bi se dobili točniji rezultati bilo bi nužno iterativno ponavljati čitav proces prethodno opisan, s novim vrijednostima neraspoloživosti grana nakon njihove revitalizacije. Tako bi, na primjer, trebalo nakon revitalizacije prvog kandidata s liste prioriteta procijeniti njegovu novu neraspoloživost, ponoviti sve proračune i odrediti novu listu prioriteta, što najčešće neće biti moguće napraviti zbog velikog broja proračuna. Iskustveno se može reći da su najviše međuovisni električki bliski vodovi, pogotovo oni koji napajaju isto čvorište mreže. Promjena neraspoloživosti jednog takvog voda utječe na indeks važnosti u EES-u ostalih kandidata za revitalizaciju, a time i na mjesto na listi prioriteta za drugi električki bliski kandidat, ali ne mijenja iznose indeksa važnosti u EES-u za ostale kandidate, pogotovo za one električki udaljene od svih kandidata prethodnih na listi.

6.3 Jedinstvena lista prioriteta za revitalizaciju

Konačna i jedinstvena lista prioriteta određuje se na temelju maksimalnog zbroja indeksa stanja i indeksa važnosti kandidata za revitalizaciju.

where:

ZiR_{k_zn} - EPS significance index of candidates k,
w_{z1} - weighting factor assigned to the age criterion $(0 \leq w_{z1} \geq 0{,}2)$,
w_{z2} - weighting factor assigned to the economic criterion $(0 \leq w_{z2} \geq 0{,}2)$,
w_{z3} - weighting factor assigned to the criterion of the risk of permanent failure $(0 \leq w_{z3} \geq 0{,}2)$,
w_{z4} - weighting factor assigned to the criterion of EPS relevancy $(0 \leq w_{z4} \geq 0{,}2)$,
w_{z5} - weighting factor assigned to the criterion of maximum marginal gain $(0 \leq w_{z5} \geq 0{,}2)$.

All fractions in the above expression assume values between 0 and 1. In order to ensure the comparison and equal treatment of condition index and significance index of the revitalization candidates in the EPS, all individual weighting factors must be defined within a range of 0 to 0,2. With the weighting factors thus defined, the maximum possible significance index amounts to 1.

The EPS significance index of the revitalization candidates depend on the unavailability of all branches in the network, so that a change in unavailability of any branch leads to different results and in the end affecting the revitalization priority list of other candidates in the network. In order to obtain more accurate results, it would be necessary to iterate the whole above described process, with new unavailability values of the branches following their revitalization. Thus, for example, after the revitalization of the first candidate on the priority list it would be necessary to assess the candidate's new priority list, which will be virtually impossible to do because of numerous calculations. Experience tells us that electrically close lines are most interdependent, especially those feeding the same network node. A change in the unavailability of such a line affects the EPS significance index of other revitalization candidates and thereby also the place on the priority list of the other electrically close candidate, but it does not change the EPS significance index amounts for other candidates, especially those electrically remote from all the candidates higher on the list.

6.3 An integrated revitalization priority list

The final and integrated priority list is compiled on the basis of the maximum sum of condition index and significance index of the revitalization candidates.

$$ZiR_k = Max\left\{ZiR_{k\_st} + ZiR_{k\_zn}\right\} \quad (43)$$

Maksimalan iznos koji može poprimiti veličina ZiR_k je 2, pri čemu se kandidati za revitalizaciju popisuju prema padajućim vrijednostima veličine ZiR_k. Najvažniji kandidat za revitalizaciju je onaj s maksimalnim iznosom ZiR_k.

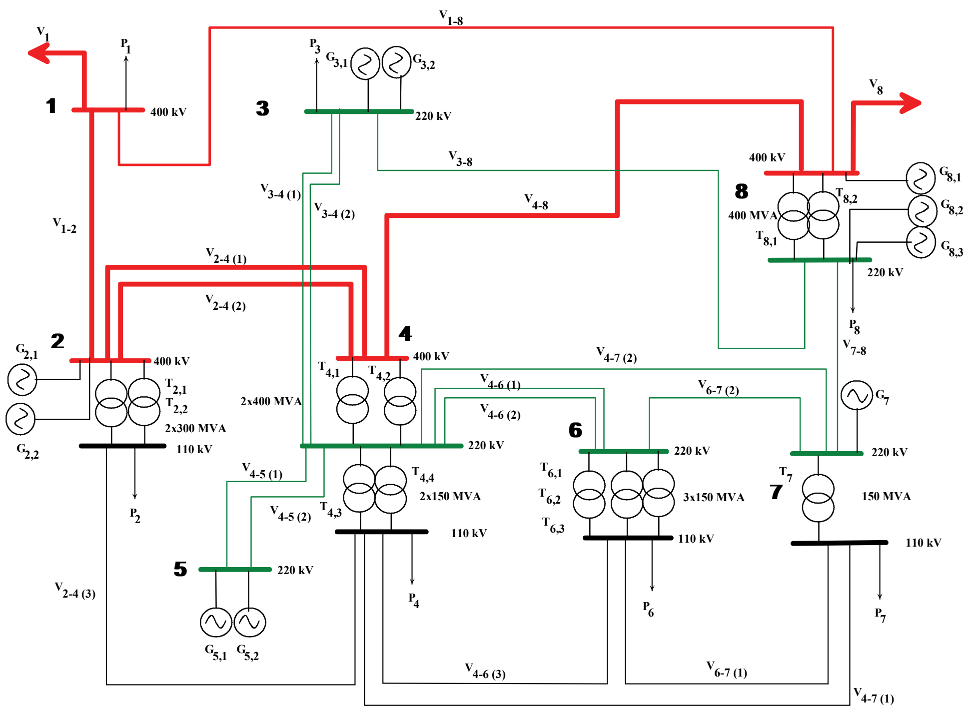
Maximum amount that the value ZiR_k can assume is 2, with the revitalization candidates being listed in the descending order of values ZiR_k. The most relevant revitalization candidate is one with a maximum amount of ZiR_k.

7 PRIMJER

Opisana metodologija za određivanje liste prioriteta za revitalizaciju vodova i transformatora u prijenosnim mrežama provjerena je na test modelu EES-a. Test model EES-a prikazan je slikom 3. Prijenosna se mreža sastoji od 400 kV (crveno), 220 kV (zeleno) i 110 kV (crno) naponskih razina. U mreži ima ukupno 19 vodova, 12 transformatora, 7 potrošača i 10 generatora. Od ukupno 31 grane, 10 vodova i transformatora starije je od 40 godina.

7 EXAMPLE

The described methodology for compiling a revitalization priority list of lines and transformers in transmission networks has been checked on the EPS Test Model. The EPS Test Model is shown in Figure 3. The transmission network consists of 400 kV (red), 220 kV (green) and 110 kV (black) voltage levels. In the network there are altogether 19 lines, 12 transformers, 7 consumers and 10 generators. Out of 31 branches, 10 lines and transformers are older than 40 years.



Slika 3 — Test model EES-a

Figure 3 — EPS Test Model

U čvorištima 1 i 8 priključeni su interkonektivni 400 kV vodovi prema susjednim EES-ima za koje se pretpostavlja da omogućavaju uvoz određene snage po definiranoj cijeni tijekom čitave godine. Susjedni EES-i u proračunima su ekvivalentirani nadomjesnim generatorima (elektranama). Pretpostavlja se da je svakim od interkonektivnih vodova prema susjednim sustavima moguće tijekom čitave godine uvoziti maksimalno 1 000 MW u interventnim situacijama po cijeni od 5,5 EURc/kWh.

In nodes 1 and 8 interconnection 400 kV lines are connected towards the neighboring EPS's presumed to allow the import of a certain power at a defined price throughout the year. The neighboring EPS's are in the calculations replaced with equivalent generators (power plants). It is presumed that with each of the interconnection lines towards the neighboring systems it is possible throughout the year to import a maximum of 1 000 MW in emergencies at a price of 5,5 EURc/kWh.

Mreža se sastoji od pet 400 kV vodova, deset 220 kV i četiri 110 kV voda. Vodovi su određeni svojim uzdužnim impedancijama (radnim otporom (R) i reaktancijom (X)), maksimalno dozvoljenom trajnom strujom u normalnom pogonu (I_{max}), te svojom neraspoloživošću (q). Neraspoloživost radi prisilnih i planiranih zastoja odgovara aritmetičkoj sredini ostvarenih vrijednosti u promatranom desetogodišnjem razdoblju. Za vodove starije od 40 godina izvršena je procjena neraspoloživosti u budućem trogodišnjem razdoblju postupkom opisanim u poglavlju 3.

U mreži postoji ukupno četiri transformatora 400/220 kV snage 400 MVA, dva transformatora 400/110 kV snage 300 MVA, te šest transformatora 220/110 kV snage 150 MVA svaki. Transformatori su određeni svojim radnim otporom (R), reaktancijom (X), prividnom snagom (S), te svojom neraspoloživošću (q). Neraspoloživost radi prisilnih i planiranih zastoja odgovara aritmetičkoj sredini ostvarenih vrijednosti u promatranom desetogodišnjem razdoblju. Za transformatore starije od 40 godina izvršena je procjena neraspoloživosti u budućem trogodišnjem razdoblju postupkom opisanim u poglavlju 3.

Ukupno vršno opterećenje za razmatrane vremenske presjeke (razdoblje $t_1 - t_3$) iznosi redom:

$P_{max}(t_1) = 2\ 094$ MW,
$P_{max}(t_2) = 2\ 125$ MW,
$P_{max}(t_3) = 2\ 157$ MW.

Raspodjela vršnog opterećenja po pojedinim čvorištima također je zadana. Zadane su i godišnje krivulje trajanja opterećenja u godini t_1, t_2 i t_3. Krivulje su podijeljene na pet dijelova i aproksimirane pravcima. Svaki od pojedinih dijelova godišnje krivulje trajanja opterećenja određen je srednjom vrijednošću opterećenja u megavatima i njegovim trajanjem u satima. Pojedinim dijelovima krivulja trajanja opterećenja pridružene su različite neraspoloživosti grana. Neraspoloživost radi prisilnih zastoja pridružena je dijelovima krivulje karakterističnim po vršnom opterećenju, te visokim i niskim zimskim opterećenjima, dok je ukupna neraspoloživost pridružena dijelovima krivulje karakterističnim po visokim i niskim ljetnim opterećenjima.

Na modelu elektroenergetskog sustava nalazi se šest elektrana od kojih su dvije nuklearne (NE, čvorišta 2 i 8), dvije su plinske kombi termoelektrane (KTE, čvorište 7 i čvorište 8), jedna termoelektrana-toplana (TE-TO, čvorište 3), te jedna akumulacijska hidroelektrana u čvorištu 5. Elektranama su poznate maksimalne snage na pragu, troškovi proizvodnje (goriva), te raspoloživost generatora koju određuju planirani i neplanirani zastoji. Akumulacijskoj hidroelektrani poznata je

The network consists of five 400 kV lines, ten 220 kV and four 110 kV lines. The lines are defined by their impedances (resistance (R) and reactance (X)), maximum permissible permanent current in normal operation (I_{max}), and their unavailability (q). Unavailability due to forced and planned outages corresponds to the arithmetic mean of realized values in the observed 10-year period. For the lines older than 40 years an assessment of unavailability in the future 3-year period has been made by applying the procedure described in section 3.

In the network there are altogether four 400/220 kV transformers of 400 MVA, two 400/110 kV transformers of 300 MVA, and six 220/110 kV transformers of 150 MVA power level each. The transformers are defined by their resistance (R), reactance (X), rated power (S) as well as their unavailability (q). Unavailability due to forced and planned outages corresponds to the arithmetic mean of realized values in the observed 10-year period. For transformers older than 40 years an assessment of unavailability in the future 3-year period has been made by applying the procedure described in section 3.

The total peak load for the examined time cross-sections (period $t_1 - t_3$) amounts in the ascending order:

$P_{max}(t_1) = 2\ 094$ MW,
$P_{max}(t_2) = 2\ 125$ MW,
$P_{max}(t_3) = 2\ 157$ MW.

The peak load distribution by nodes is also given, and so are the annual load duration curves in year t_1, t_2 and t_3. The curves are divided into five parts and straight line approximated. Each of the parts of the annual load duration curve is defined by the mean value of load in megawatts and its duration in hours. To the particular parts of the load duration curves various branch unavailabilities are attached. Unavailability due to forced outages is attached to the parts of the curve characterized by their by peak load and high and low winter loads, whereas the total unavailability is attached to the parts of the curve characterized by high and low summer loads.

On the EPS model there are six power plants of which two are nuclear (NPP, nodes 2 and 8), two are combined-cycle power plants (CCGT, node 7 and node 8), one is a combined heat and electricity production power plant (CHP, node 3), and one is a storage hydro plant in node 5. Known about the power plants are installed powers, costs of generation (fuel) and the generator availability defined by planned and unplanned outages. Known about the storage hydro plant are installed power and engagement corresponding to zero generation costs.

instalirana snaga i angažmanom koji odgovara nultim troškovima proizvodnje.

Polazni angažman akumulacijske hidroelektrane (HE) u čvorištu 5 određen je na osnovi prosječnih mjesečnih dotoka u promatranom razdoblju. Tako određena angažirana snaga hidroelektrane predstavlja gornju granicu proizvodnje uz troškove jednake nuli, pa će svaki dodatni angažman akumulacijske hidroelektrane (u slučaju preraspodjele proizvodnje na modelu radi izbjegavanja preopterećenja pojedinih grana prijenosne mreže) značiti povećanje troškova dodatne hidro proizvodnje i ukupnih troškova rada sustava. Neplanirano pražnjenje akumulacije u tom slučaju donosi dodatni trošak koji je procijenjen na 5 EURc/kWh, što znači da će se eventualno preopterećenje pojedine grane mreže pokušati izbjeći preraspodjelom termo proizvodnje u sustavu, a tek onda dodatnim pražnjenjem akumulacije hidroelektrane u čvorištu 5.

Vjerojatnosti nastanka pojedinih hidroloških stanja iznose:

— normalna hidrologija: $q_{nh} = 0{,}5$,
— suha hidrologija: $q_{sh} = 0{,}2$,
— vlažna hidrologija: $q_{vh} = 0{,}3$.

U slučaju nemogućnosti otklanjanja preopterećenja u mreži, algoritam računa minimalno potrebnu redukciju opterećenja kako bi sve grane mreže ostale opterećene unutar dozvoljenih granica. Redukcija opterećenja izaziva određeni trošak, a kao jedinični trošak neisporučene električne energije definirana je vrijednost od 3 EUR/kWh.

Kandidati za zamjene i rekonstrukcije su (jedinice starije od 40 godina):

$V_{3-4(1)}$ – 220 kV vod između čvorišta 3 i 4,
V_{3-8} – 220 kV vod između čvorišta 3 i 8,
$V_{4-7(2)}$ – 220 kV vod između čvorišta 4 i 7,
$V_{6-7(2)}$ – 220 kV vod između čvorišta 6 i 7,
$V_{4-6(3)}$ – 110 kV vod između čvorišta 4 i 6,
$V_{6-7(1)}$ – 110 kV vod između čvorišta 6 i 7,
$T_{4,3}$ – 220/110 kV transformator u čvorištu 4,
$T_{4,4}$ – 220/110 kV transformator u čvorištu 4 (paralelan prethodnom),
$T_{6,1}$ – 220/110 kV transformator u čvorištu 6,
T_{7} – 220/110 kV transformator u čvorištu 7.

Za svaki promatrani vremenski presjek formirana su tri scenarija ovisna o hidrologiji (normalna, suha i vlažna hidrologija). Ukupno je analizirano 9 scenarija unutar promatrana tri vremenska razdoblja te su izvršene probabilističke simulacije rada sustava za različite visine neraspoloživosti pojedinih grana kandidata za revitalizaciju.

The starting engagement of the storage hydro plant (HPP) in node 5 is defined on the basis of average monthly inflows over the observed period. The engaged power of a hydro plant thus defined represents the upper limit of generation at zero cost, so each additional engagement of a storage hydro plant (in case of generation redistribution on the model in order to avoid overloads of particular transmission network branches) will entail an increase in the cost of additional hydro generation and the overall system operation costs. Unplanned discharging of the storage in that case brings with it an additional cost estimated at 5 EURc/kWh, meaning that an attempt will be made to avoid overloading a branch through redistribution of thermo generation in the system and only then by additional discharging of the hydro plant storage in node 5.

The probabilities of the occurrence of particular hydrological conditions are:

— normal hydrology: $q_{nh} = 0{,}5$,
— dry hydrology: $q_{sh} = 0{,}2$,
— wet hydrology: $q_{vh} = 0{,}3$.

If it is impossible to eliminate overloads in the network, the algorithm computes minimum required load reduction so that all branches may stay loaded within permissible margins. Load reduction involves a certain cost. The value of 3 EUR/kWh is defined as the unit cost of undelivered electricity.

Replacement and reconstruction candidates are (units older than 40 years):

$V_{3-4(1)}$ – 220 kV line between nodes 3 and 4,
V_{3-8} – 220 kV line between nodes 3 and 8,
$V_{4-7(2)}$ – 220 kV line between nodes 4 and 7,
$V_{6-7(2)}$ – 220 kV line between nodes 6 and 7,
$V_{4-6(3)}$ – 110 kV line between nodes 4 and 6,
$V_{6-7(1)}$ – 110 kV line between nodes 6 and 7,
$T_{4,3}$ – 220/110 kV transformer in node 4,
$T_{4,4}$ – 220/110 kV transformer in node 4 (parallel to the previous one),
$T_{6,1}$ – 220/110 kV transformer in node 6,
T_{7} – 220/110 kV transformer in node 7.

For each observed time cross-section three scenarios are defined, depending on the hydrological conditions (normal, dry and wet hydrology). A total of 9 scenarios have been analyzed with the observed three-year period of time and the probabilistic system operation simulations have been carried out for different unavailability levels of the particular branches of the revitalization candidates.

Tablica 2 – Prosječno povećanje očekivanih godišnjih operativnih troškova rada EES-a radi slabosti mreže uz različite iznose neraspoloživosti kandidata za revitalizaciju (EUR)
Table 2 – Average increase in the expected annual operating costs of the EPS due to the weaknesses of the network, at different levels of unavailability of the revitalization candidates (EUR)

Kandidati za *ZiR* / Candidates for revitalization	$\overline{OC_i(j)-OC_{i,k}(j)}$	$\overline{OC_i(j)-OC'_{i,k}(j)}$	$\overline{OC_{i,k1}(j)-OC_i(j)}$	$\overline{OC_{i,k1}(j)-OC_{i,k0}(j)}$	$\overline{M_{i,k}(j)}$
$V_{3-4(1)}$	0	0	2 949	2 949	0
V_{3-8}	4	4	7 984	7 988	0
$V_{4-7(2)}$	0	0	5 686	5 704	7
$V_{6-7(2)}$	0	0	23	23	0
$V_{4-6(3)}$	0	0	122 092	122 092	0
$V_{6-7(1)}$	0	119	86 276	88 045	0
$T_{4,3}$	537	537	1 541 123	1 541 044	205
$T_{4,4}$	25	25	1 422 160	1 422 245	0
$T_{6,1}$	497	497	1 961 804	1 962 301	0
T_7	1 859	1 859	1 452 287	1 454 145	0
Max	1 859	1 859	1 961 804	1 962 301	205

Tablica 2 prikazuje prosječna povećanja očekivanih godišnjih operativnih troškova rada EES-a radi slabosti mreže za sve ispitane scenarije ovisne o razmatranom vremenskom presjeku i hidrološkom stanju uz različite iznose neraspoloživosti kandidata za revitalizaciju, uvažavajući pri tom vjerojatnosti nastanka pojedinih hidroloških stanja. U zadnjem retku tablice prikazane su maksimalne vrijednosti u pojedinim razmatranim kategorijama.

Jedinstvena lista prioriteta za zamjene i rekonstrukcije izrađuje se na temelju izraza (43). Svi težinski faktori postavljeni su na iznos od 0,2. Listu prioriteta prikazuje tablica 3. Najvažniji kandidat za revitalizaciju prema kriterijima i metodologiji razvijenoj u ovom radu je 220/110 kV transformator 3 u čvorištu 4. Zbroj pripadnih indeksa stanja i važnosti u EES-u za ovaj transformator iznosi 1,137 od ukupno mogućeg najvećeg zbroja od 2. Slijedi ga 220/110 kV transformator u čvorištu 7 sa zbrojem indeksa stanja i važnosti od 1,131. Zadnji na listi prioriteta je 220 kV vod između čvorišta 6 i 7.

Table 2 shows the average increases in the expected annual operating costs of the EPS due to the weaknesses of the network for all tested scenarios dependent on the reviewed time cross-section and the hydrological conditions at different levels of the unavailability of the revitalization candidates, with the probabilities of the occurrence of particular hydrological conditions being taken into consideration. In the last row of the above table the maximum values by studied categories are shown.

The integrated revitalization priority list is compiled on the basis of expression (43). All weighting factors are set on the amount of 0,2. The priority list is shown in Table 3. The most important revitalization candidate according to the criteria and methodology developed in this work is the 220/110 kV transformer 3 in node 4. The sum of the related condition and the EPS significance indices for that transformer amounts to 1,137 out of the highest possible sum of 2. It is followed by the 220/110 kV transformer in node 7 with the sum of the condition and significance indices amounting to 1,131. The last on the priority list is the 220 kV line between nodes 6 and 7.

Tablica 3 – Konačna lista prioriteta za revitalizaciju (test model EES)
Table 3 – Final revitalization priority list (EPS Test Model)

Kandidati za *ZiR* / Candidates for revitalization	ZiR_k	Poredak / Order
$T_{4,3}$	1,137	1
T_7	1,131	2
$T_{6,1}$	0,909	3
$V_{4-6(3)}$	0,831	4
$V_{6-7(1)}$	0,740	5
$T_{4,4}$	0,605	6
$V_{4-7(2)}$	0,401	7
$V_{3-4(1)}$	0,358	8
$V_{6-7(2)}$	0,287	9
V_{3-8}	0,243	10

8 ZAKLJUČAK

Pristup određivanju liste prioriteta za revitalizaciju vodova i transformatora u prijenosnoj mreži, predložen ovim istraživanjem, različit je od pristupa drugih istraživača objavljenih u dostupnoj literaturi. Osnovna karakteristika predloženog postupka i njegova prednost u odnosu na ostale metode je što nastoji integrirati rezultate dijagnostike i ispitivanja stvarnog stanja jedinica prijenosne mreže i njihove uloge u toj mreži, određene na temelju probabilističkih simulacija rada EES-a i očekivanih troškova njegova rada pri različitim razinama neraspoloživosti promatranih jedinica, u jedinstveni skup te na osnovi postavljenih kriterija i metodologije istraživanja odrediti jedinstvenu listu prioriteta za revitalizaciju.

Na taj se način na temelju troškovnih principa, tehničkih karakteristika, stohastičke prirode EES-a i statističkih podataka određuje optimalan plan revitalizacije kapitalne opreme u prijenosnoj mreži, kao što su vodovi i transformatori, te doprinosi povećanju pouzdanosti rada EES-a, kao i sigurnosti opskrbe potrošača električnom energijom.

Predloženom metodom također se unaprjeđuje postupak planiranja razvoja prijenosnih elektroenergetskih mreža, budući da u dosadašnjim metodama nije u obzir uziman aspekt starosti opreme u prijenosnoj mreži. Također se omogućava sagledavanje eventualnih potreba za izmjenom karakteristika pojedine opreme kroz aktivnosti na revitalizaciji, a ovisno o budućim potrebama EES-a. Na taj se način pridonosi boljem iskorištenju postojećih koridora i ubla-

8 CONCLUSION

The approach to the priority list to be defined for the revitalization of lines and transformers in a transmission network proposed in the present research differs from the approach advocated by other researchers in the accessible literature. The basic feature of the proposed procedure and its advantage in relation to other methods is that it tries to integrate the results of the diagnostics and testing of the real condition of the transmission network units and their role in the network, defined on the basis of probabilistic simulations of the EPS's operation and the expected costs of its operation at different unavailability levels of the observed units, into a common group and, based on the set criteria and investigation methodology, to define a single revitalization priority list.

In this way, based on cost principles, technical characteristics, the stochastic nature of the EPS and statistics, an optimum plan for the revitalization of capital equipment in the transmission network, such as the lines and transformers, is defined, and a contribution made to an increased operating reliability of the EPS, as well as to the security of supplying consumers with electricity.

The proposed method also improves the procedure of planning the development of electric power transmission networks, because the existing methods do not make allowance for the age aspect of transmission network equipment. What is also made possible is identifying likely needs for modification of the characteristics of some equipment through revitalization activities and in dependence on the EPS's future needs. In this way it is contributed to žavanju prostornih ograničenja koji zbog porasle ekološke svijesti predstavljaju sve veći problem u razvoju EES-a.

Metodologija i kriteriji definirani u ovom radu predstavljaju doprinos rješavanju problema izrade jedinstvene liste prioriteta zamjene i izgradnje jedinica mreže u uvjetima neizvjesnosti koji postoje unutar otvorenih tržišta električnom energijom.

better utilization of the existing corridors aimed to mitigate the effect of spatial constraints which, due to raised environmental awareness, pose an increasing problem to the EPS development.

The methodology and the criteria defined in the present work are meant to be a useful tool in addressing the problem of compiling an integrated priority list of replacement and construction of network units under the conditions of uncertainty existing on open electricity markets.

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