MODEL CRPNO-AKUMULACIJSKE (REVERZIBILNE) HIDROELEKTRANE U MODELU POUZDANOSTI I RASPOLOŽIVOSTI ELEKTROENERGETSKOG SUSTAVA

THE PUMPED-STORAGE HYDRO POWER PLANT MODEL WITHIN IN THE POWER SYSTEM RELIABILITY AND AVAILABILITY MODEL

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U ovom radu izlaže se model kojim se u proračune pouzdanosti i raspoloživosti elektroenergetskog sustava uključuje crpno-akumulacijska hidroelektrana, a zatim i model utjecaja rizika nedostatka dotoka i zaliha vode na planiranje rada takvih postrojenja u okviru programskih sustava za operativna planiranja za vremenska razdoblja do razine godinu dana unaprijed. Utjecaj neizvjesnosti pojava dotoka veže se za karakteristike vodotoka na kojima su izgrađeni akumulacijski bazeni i hidroelektrana, ali i za radne cikluse i mogući način rada u sustavu.

This paper deals with a model that comprises the pumped-storage hydro power plants in the power system reliability and availability calculations, as well as a model of the impact of inflow deficiency and water storage risks on the operational planning of such plants within the framework of operational planning systems for periods of up to one year. The impact of inflow uncertainties is related to the characteristics of watercourses where the water storage reservoirs and hydro power plants are built, but also to the operation cycles and possible operation modes in the system.

Ključne riječi: model crpno-akumulacijske hidroelektrane, model pouzdanosti i raspoloživosti sustava, rizik nedostatka dotoka

Keywords: inflow deficiency risk, power system reliability and availability model, pumped-storage hydro power plant model

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1 UVOD

Kada je riječ o problemu uključivanja crpno-akumulacijske hidroelektrane u model pouzdanosti i raspoloživosti elektroenergetskog sustava, u njemu je nužno razlikovati dvije osnovne komponente ili dva dijela. S jedne strane, radi se o osnovnom modelu crpno-akumulacijskog pogona koji je moguće modelirati na više načina, bilo složenim modelima koji uključuju više mogućih različitih stanja i njihovih veza, bilo višestrukim kombiniranjem jednostavnih modela za pojedine funkcije [1], [2] i [5], a s druge strane je uvjetovanost pogona takvih postrojenja njihovom ulogom u sustavu i neizvjesnošću pojave dotoka i stanja gornje i donje akumulacije [3], [4], [6], [8], [9] i [10].

Kod osnovnih modela kod kojih se generatorski i crpni pogon modeliraju odvojeno, osnovni nedostatak pristupa proizlazi iz nemogućnosti da se usklade razdiobe vjerojatnosti pojedinih grupa stanja koje se računaju na različitim osnovama. Nadalje, nije moguće jednostavno modelirati brzi prelazak iz crpnog u generatorski pogon i eventualno obrnuto, a tu je i nemogućnost da se to izvede zbog odgovarajućeg kvara. U ovom radu odabran je pristup kojim se crpno-akumulacijski pogon modelira jedinstvenim modelom s osam stanja u kojem se mogu identificirati stanja generatorskog i crpnog pogona, ali i slučajevi kvarova jedinice pri startu i tijekom pogona, odnosno prelasci iz jednog pogona u drugi uz pripadnu vjerojatnost kvara koja ima utjecaja na raspoloživost sustava [7], [10] i [12].

Rad svakog proizvodnog objekta u elektroenergetskom sustavu prati rizik da će prije ili tijekom ulaska u pogon, odnosno tijekom pogona, ostati bez primarne pogonske energije, u ovom slučaju vode. Taj rizik vezan je za neizvjesnost pojave dotoka i stanja gornje i donje akumulacije. U pravilu, kod hidroelektrana rizik zbog neizvjesnosti dotoka i stanja akumulacije puno je izraženiji od rizika pojave kvara. Kod crpno-akumulacijske hidroelektrane pojavljuje se i problem složenog radnog ciklusa i ovisnosti o prilikama u sustavu i načinu rada ostalih proizvodnih postrojenja [1], [10], [11] i [12].

2 OSNOVNI MODEL JEDINICE ZA CRPNO-AKUMULACIJSKI POGON

Kako je u uvodu istaknuto, crpno-akumulacijski pogon moguće je modelirati na više načina, dakle modelima koji uključuju više mogućih

1 INTRODUCTION

Regarding the problem of including the pumped-storage hydro power plants in the power system reliability and availability model, it is necessary to distinguish two different basic components or two parts. On one hand, there is the basic model of pumped-storage drive that can be modelled in several different ways, either with complex models involving several different states and their connections or through multiple combination of simple models for specific functions [1], [2] and [5]. On the other hand, there is the dependence of the drive of such plants on their role in the system and the uncertainty of inflows and the status of the upper and lower reservoir [3], [4], [6], [8], [9] and [10].

With the basic models, where the generator and pump drive are modelled separately, the fundamental shortcoming comes from the lack of possibility to balance the probability distribution of specific groups of states that are calculated on different bases. Further, it is not easy to model a quick transition from the pumped to the generator drive and possibly vice versa, and there is also the impossibility to accomplish this due to a defect. This work has opted for an approach whereby the pumped-storage drive is modelled with a single 8-state model in which the states of generator and pumped drive can be identified, as well as cases of the unit's failure at start-up and during the operation, i.e. the alterations from one drive to another along with the pertaining failure probability having an impact on the system availability [7], [10] and [12].

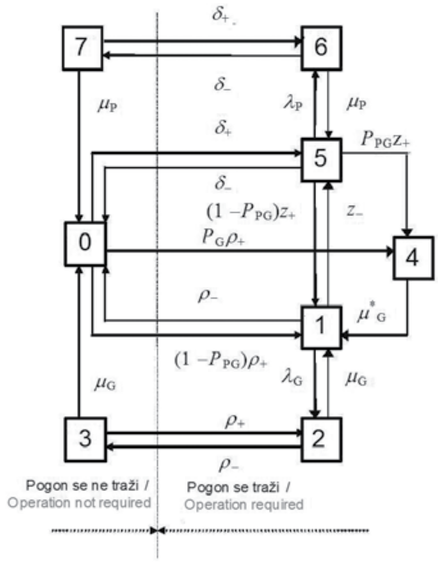
The operation of any generating plant in the power system is exposed to the risk of running short of the primary drive energy before or in the start-up process or during operation, in this case water. That risk is linked to the uncertainty of inflow and the upper and lower reservoir levels. As a rule, with hydro power plants the risk associated with uncertain inflows and reservoir levels is much higher than the failure risk. With the pumped-storage hydro power plants there is also the problem of a complex operation cycle and dependence on the conditions prevailing in the system and the operation mode of other generating plants [1], [10], [11] and [12].

2 THE BASIC MODEL OF A PUMPED-STORAGE DRIVE UNIT

As emphasized in the Introduction, the pumped-storage drive can be modelled in several ways, i.e.

različitih stanja i njihovih veza, ali i kombiniranjem odgovarajućih jednostavnih modela jedinica. U ovom radu izloženi su elementi modela kojim se pogon crpno-akumulacijske hidroelektrane modelira jedinstvenim modelom s osam stanja u kojem se mogu identificirati stanja generatorskog i crpnog pogona, ali i slučajevi kvarova jedinice pri startu i tijekom pogona, odnosno prelasci iz jednog pogona u drugi uz pripadnu vjerojatnost kvara koja ima utjecaja na raspoloživost sustava (slika 1).

with models that include several possible different states and their links but also by combining the unit's corresponding simple models. This paper presents the elements of the unique 8-state model where the states of generator and pumped drive can be identified as well as cases of start-up and operation incurred failures in the unit, i.e., the alternations from one drive to another with the pertaining failure probability having an impact on the system's availability (Figure 1).



Slika 1 – Model jedinice za crpno-akumulacijski pogon
Figure 1 – State-space diagram for a pumped-storage unit

Oznake na slici 1:

- 0 – stanje rezervnog isključenja jedinice.
- 1 – stanje generatorskog pogona ,
- 2 – stanje kvara nastalog tijekom proizvodnje,
- 3 – stanje popravka nakon kvara nastalog tijekom proizvodnje, a kad se pogon ne traži,
- 4 – stanje kvara pri ulasku generatora u pogon,
- 5 – stanje crpnog pogona,
- 6 – stanje kvara nastalog tijekom crpljenja,
- 7 – stanje popravka kad se pogon ne traži, a nakon kvara nastalog tijekom crpljenja,
- ρ_+ / ρ_- – učestalost pojave/prestanka potrebe za generatorskim pogonom,
- δ_+ / δ_- – učestalost pojave/prestanka potrebe za crpljenjem vode u gornji bazen,
- λ_G / μ_G – učestalost kvara/popravka jedinice u svezi s generatorskim pogonom,
- μ_G^* – učestalost popravka jedinice nakon kvara pri ulasku u proizvodni pogon,
- λ_P / μ_P – učestalost kvara/popravka jedinice u svezi s crpnim pogonom,

Legend (Figure 1):

- 0 – ready for service (reserve) unit state,
- 1 – generator drive state,
- 2 – generation incurred failure state,
- 3 – repair after generation incurred failure state while operation is not required,
- 4 – generator start operation incurred failure state,
- 5 – pump drive state,
- 6 – pump drive operation incurred failure state,
- 7 – repair after pump drive operation incurred failure state while operation is not required,
- ρ_+ / ρ_- – transition rate of on/off generator drive,
- δ_+ / δ_- – transition rate of on / off water pump ing into upper reservoir,
- λ_G / μ_G – transition rate of unit failure / repair related to generator drive,
- μ_G^* – transition rate of unit repair of start operation incurred failure,
- λ_P / μ_P – transition rate of unit failure / repair related to pump drive,

z_+ / z_- – učestalost pojave/prestanka potrebe za prelaskom iz crpnog u proizvodni pogon,
P_G – vjerojatnost kvara pri startu generatora,
P_{PG} – vjerojatnost kvara jedinice pri prijelazu iz crpnog u proizvodni pogon.

z_+ / z_- – transition rate of alternation from pump to generation drive,
P_G – failure probability in generator starting-up,
P_{PG} – failure probability in alternation from pump to generation drive.

Broj i tip kvarova jedinice izrazito su ovisni o radnom ciklusu jedinice, pogotovo što se kod generatorskog načina rada radi o vršnom pogonu kod kojeg se kvarovi događaju pri samom startu, tijekom pogona ili pri prijelazu iz crpnog pogona u generatorski, a traju tijekom potrebe za pogonom ili i nakon što ta potreba prestane. Radni ciklusi utječu na učestalosti prijelaza jedinice iz jednog stanja u drugo, tako da je nužno eksplicitno razlikovanje učestalosti nastanka ili prestanka potrebe za određenim pogonskim stanjem, promjenama pogonskih stanja, kvarova pri startu, kvarova tijekom pogona ili pri prijelazu iz jednog pogonskog stanja u drugo, te učestalosti popravaka nakon kvarova iz različitih stanja.

Sustav linearnih diferencijalnih jednadžbi Markovljeva procesa prema slici 1 ima oblik:

The number and type of unit failures are markedly dependent on the unit operation cycle, especially in the generator operation mode where failures occur during the start-up in conditions of peak load, operation and drive-to-drive alternation incurred failures and last as long as there is a need for operation and occasionally after the need ends. The operation cycles influence the transition rate of alternation from one drive to another, so that it is necessary to clearly distinguish between the transition rate of the occurrence or termination of the need for a specific drive operation, alternation of drives, failures at start-up position, failures during operation or during drive-to-drive alternations, as well as the rate of repairs after failures in different states.

The system of linear differential equations of the Markov process according to Figure 1 has the following form:

$$\begin{aligned}
\dot{P}_0(t) &= -(\rho_+ + \delta_+)P_0 + \rho_- P_1 + \mu_G P_3 + \delta_- P_5 + \mu_P P_7 \\
\dot{P}_1(t) &= (1-P_G)\rho_+ P_0 - (\rho_- + z_- + \lambda_G)P_1 + \mu_G P_2 + \mu_G^* P_4 + (1-P_{PG})z_+ P_5 \\
\dot{P}_2(t) &= \lambda_G P_1 - (\rho_- + \mu_G)P_2 + \rho_+ P_3 \\
\dot{P}_3(t) &= \rho_- P_2 - (\rho_+ + \mu_G)P_3 \\
\dot{P}_4(t) &= P_G \rho_+ P_0 - \mu_G^* P_4 + P_{PG} z_+ P_5 \\
\dot{P}_5(t) &= \delta_+ P_0 + z_- P_1 - (\delta_- + \lambda_P + z_+)P_5 + \mu_P P_6 \\
\dot{P}_6(t) &= \lambda_P P_5 - (\delta_- + \mu_P)P_6 + \delta_+ P_7 \\
\dot{P}_7(t) &= \delta_- P_6 - (\delta_+ + \mu_P)P_7 \,.
\end{aligned} \tag{1}$$

Početni uvjeti jesu:

The start-up conditions are:

$$\begin{aligned}
&P_0(0)=1,\ P_1(0)=0,\ P_2(0)=0,\ P_3(0)=0, \\
&P_4(0)=0,\ P_5(0)=0,\ P_6(0)=0,\ P_7(0)=0.
\end{aligned} \tag{2}$$

Traži se stacionarno rješenje, tj. rješenje kada je:

A stationary solution is sought, i.e., one where:

$$\dot{P}_n(t)=0,\ n=0,\ 1,\ 2,\ 3,\ 4,\ 5,\ 6,\ 7.$$

Uz uvjete (2), sustav (1) poprima novi oblik:

With conditions (2), the system (1) assumes a new form:

$$
\begin{aligned}
0 &= -(\rho_+ + \delta_+)P_0 + \rho_-\ P_1 + \mu_G P_3 + \delta_-\ P_5 + \mu_P P_7 \\
0 &= (1-P_G)\ \rho_+\ P_0 - (\rho_- + z_- + \lambda_G)P_1 + \mu_G P_2 + \mu_G^* P_4 + (1-P_{PG})\ z_+\ P_5 \\
0 &= \lambda_G P_1 - (\rho_- + \mu_G)P_2 + \rho_+\ P_3 \\
0 &= \rho_-\ P_2 - (\rho_+ + \mu_G)P_3 \\
0 &= P_G\ \rho_+\ P_0 - \mu_G^* P_4 + P_{PG}\ z_+\ P_5 \\
0 &= \delta_+\ P_0 + z_-\ P_1 - (\delta_- + \lambda_P + z_+)P_5 + \mu_P P_6 \\
0 &= \lambda_P P_5 - (\delta_- + \mu_P)P_6 + \delta_+ P_7 \\
0 &= \delta_-\ P_6 - (\delta_+ + \mu_P)P_7\ \ .
\end{aligned}
\tag{4}
$$

Uz jednadžbu identiteta:

With the identity equation:

$$
P_0 + P_1 + P_2 + P_3 + P_4 + P_5 + P_6 + P_7 = 1 \tag{5}
$$

stacionarno rješenje, tj. stacionarne vjerojatnosti stanja jesu:

the stationary solution, i.e., stationary probabilities of the state are:

$$
\begin{aligned}
P_0 &= \frac{\rho_-\ \delta_+\ \lambda_G \lambda_P \{B[F(HM+KJ)+I(DM+GK)] + C[KEI+L(HF+DI)]\}}{\Delta} \\
P_1 &= \frac{\delta_-\ \mu_G \lambda_P (\rho_+ + \rho_- + \mu_G) A[F(HM+KJ)+I(DM+GK)]}{\Delta} \\
P_2 &= \frac{\delta_-\ \lambda_G \lambda_P (\rho_+ + \mu_G) A[F(HM+KJ)+I(DM+GK)]}{\Delta} \\
P_3 &= \frac{\delta_-\ \lambda_G \lambda_P \rho_-\ A[F(HM+KJ)+I(DM+GK)]}{\Delta} \\
P_4 &= \frac{\delta_-\ \lambda_G \lambda_P \rho_-\ A[E(HM+KJ)+L(DJ-GH)]}{\Delta} \\
P_5 &= \frac{\rho_-\ \lambda_G \mu_P (\delta_+ + \delta_- + \mu_P) A[KEI+L(HF+DI)]}{\Delta} \\
P_6 &= \frac{\rho_-\ \lambda_G \mu_P (\delta_+ + \mu_P) A[KEI+L(HF+DI)]}{\Delta} \\
P_7 &= \frac{\rho_-\ \lambda_G \mu_P \delta_-\ A[KEI+L(HF+DI)]}{\Delta}.
\end{aligned}
\tag{6}
$$

gdje je:

where:

$$
\begin{aligned}
\Delta = {} & \rho_-\ \lambda_G [KEI+L(HF+DI)] \cdot \\
& \{(A+C)\delta_-\ \lambda_P + A[\lambda_P(\delta_+ + \mu_P) + \mu_P(\delta_+ + \delta_- + \mu_P)]\} \\
& + \delta_-\ \lambda_P [F(HM+KJ)+I(DM+GK)] \cdot \\
& \{(A+B)\rho_-\ \lambda_G + A[\lambda_G(\rho_+ + \mu_G) + \mu_G(\rho_+ + \rho_- + \mu_G)]\}
\end{aligned}
$$

$$+\delta_- \rho_+ \lambda_P \lambda_G A\left[E(HM+KJ)+L(DJ-GH)\right]$$
$$A=\lambda_G \lambda_p(\rho_+ +\delta_+)$$
$$B=\mu_G \lambda_p(\rho_+ +\rho_- +\mu_G+\lambda_G) \tag{7}$$
$$C=\lambda_G \mu_p(\delta_+ +\delta_- +\mu_p+\lambda_p)$$
$$D=(1-P_{PG})\rho_+ \rho_- \delta_- \lambda_G \lambda_p$$
$$E=\delta_- \mu_G \lambda_p [\rho_- (\rho_+ +\rho_- +\mu_G+\lambda_G+z_-)+z_- (\rho_+ +\mu_G)]$$
$$F=\rho_- \delta_- \mu_G^* \lambda_G \lambda_p$$
$$G=(1-P_{PG})\rho_- \lambda_G \mu_p z_+ (\delta_+ +\delta_- +\mu_p)$$
$$H=P_G \rho_+ \delta_- \lambda_p$$
$$I=\delta_- \mu_G^* \lambda_p$$
$$J=P_{PG} \mu_p z_+ (\delta_+ +\delta_- +\mu_p)$$
$$K=\rho_- \delta_- \delta_+ \lambda_G \lambda_p$$
$$L=\delta_- \mu_G \lambda_p z_- (\rho_+ +\rho_- +\mu_G)$$
$$M=\rho_- \lambda_G \mu_p[z_+ (\delta_+ +\delta_- +\mu_P)+\delta_- (\delta_+ +\delta_- +\mu_P+\lambda_P)].$$

Znatno pojednostavljenje rješenja moguće je uvaže li se ranije iznesene pretpostavke koje vrijede općenito za objekte elektroenergetskog sustava, a to su da su vremena ostajanja u stanjima 2, 3, 4, 6 i 7 znatno kraća od vremena ostajanja u stanjima pogonske spremnosti 0, 1 i 5, odnosno da su učestalosti prijelaza u stanja pogonske spremnosti znatno veće od učestalosti ulazaka u stanja pogonske nespremnosti. Uz zanemarivu pogrešku koja se pritom čini, postupak računanja vjerojatnosti pojedinih stanja postaje znatno lakši i jednostavniji. Dakle:

It is possible to greatly simplify the solution by taking into account the previous assumptions which generally apply to power system facilities and according to which the periods of remaining in states 2, 3, 4, 6 and 7 are much shorter than the periods of remaining in the operational stand-by conditions 0, 1 and 5, meaning that the transition rates of alternation into the stand-by operation condition are significantly higher than the transition rate of entering into non-operation conditions. With a marginal error appearing in the process, the calculation routine of specific state probabilities becomes much easier. Hence:

$$P_0=\frac{1}{\Delta^*}\mu_G \mu_G^* \mu_p (\rho_+ +\rho_- +\mu_G)(\delta_+ +\delta_- +\mu_P)\cdot$$
$$[\rho_+ \rho_- (\delta_- +z_+) (1-P_G)+\delta_+ \delta_- (\rho_- +z_-)]$$
$$P_1=\frac{1}{\Delta^*}\rho_+ (\rho_+ +\rho_- +\mu_G) (\delta_+ +\delta_- +\mu_P) (\rho_+ +\delta_+) (\delta_- +z_+) (1-P_G)$$
$$P_2=\frac{1}{\Delta^*}\rho_+ \lambda_G \mu_G^* \mu_p (\rho_+ +\mu_G) (\delta_+ +\delta_- +\mu_P) (\rho_+ +\delta_+) (\delta_- +z_+) (1-P_G)$$
$$P_3=\frac{1}{\Delta^*}\rho_+ \rho_- \lambda_G \mu_G^* \mu_p (\delta_+ +\delta_- +\mu_P) (\rho_+ +\delta_+) (\delta_- +z_+) (1-P_G)$$
$$P_4=\frac{1}{\Delta^*}\mu_G \mu_G^* (\rho_+ +\delta_+) (\rho_+ +\rho_- +\mu_G) (\delta_+ +\delta_- +\mu_P) (\rho_- +z_-)\cdot$$
$$\cdot[\rho_+ (\delta_- +z_+)P_G+\delta_+ z_+ P_{PG}] \tag{8}$$
$$P_5=\frac{1}{\Delta^*}\delta_+ \mu_G \mu_G^* \mu_P(\rho_+ +\delta_+) (\rho_+ +\rho_- +\mu_G) (\delta_+ +\delta_- +\mu_P) (\rho_- +z_-)$$
$$P_6=\frac{1}{\Delta^*}\delta_+ \mu_G \mu_G^* \lambda_P(\rho_+ +\delta_+) (\delta_+ +\mu_P) (\rho_+ +\rho_- +\mu_G) (\rho_- +z_-)$$
$$P_7=\frac{1}{\Delta^*}\delta_+ \delta_- \mu_G \mu_G^* \lambda_P(\rho_+ +\delta_+) (\rho_+ +\rho_- +\mu_G) (\rho_- +z_-)$$

$$\Delta^* = (\delta_+ + \delta_- + \mu_P)\ (\rho_+ + \rho_- + \mu_G)\rangle \mu_G\ \mu_G^*\ \mu_p\ [\rho_+\ \rho_-(\delta_- + z_+)\ (1 - P_G) +$$
$$\delta_+\ \delta_-\ (\rho_- + z_-)] + \delta_+\ \mu_G^*\ \mu_P\ (\rho_+ + \delta_+)\ (\delta_- + z_+)\ (\mu_G + \lambda_G)\ (1 - P_G) +$$
$$(\rho_+ + \delta_+)\ (\rho_- + z_-)\{\mu_G\ \mu_p\ [\rho_+\ (\delta_- + z_+)P_G + \delta_+\ z_+\ P_{PG}] + \delta_+\ \mu_G\ \mu_G^*(\lambda_P + \mu_P)\}\langle .$$

Grupiranja stanja provode se po ranije utvrđenim pravilima. Parametri modela računaju se iz pogonske statistike broja ulazaka i izlazaka iz svakog stanja, trajanja svakog pojedinog stanja ili grupe stanja, te nastanku ili prestanku potrebe za proizvodnjom ili crpljenjem. Međutim, za razliku od svih prethodnih modela i slučajeva, ovdje se mogu jasno razlikovati dvije zasebne grupe stanja i u funkcionalnom smislu. To su grupa stanja generatorskog pogona, tj. proizvodnje električne energije tijekom sati vršnog opterećenja sustava (1, 2 i 3) i grupa stanja crpljenja vode iz donjeg u gornji akumulacijski bazen tijekom sati minimalnog opterećenja sustava (5, 6 i 7). Izrazi za vjerojatnosti stanja unutar tih grupa razlikuju se tek u jednom ili dva člana, čime se može dodatno znatno pojednostavniti računanje vjerojatnosti stanja unutar tih dviju osnovnih grupa stanja. Ti dodatni odnosi koji olakšavaju računanje vjerojatnosti stanja glase:

Grouping of states is carried out in accordance with the previously established rules. The model parameters are calculated from operational statistics showing the number of appearances and terminations of each state, the duration of each particular state or group of states as well the appearance or termination of the need for generation or pumping. However, unlike the previous models and cases, here it is possible to clearly distinguish between two separate groups of states in the functional sense as well. These are the group of generator drive, i.e., electricity generation during peak load hours (1, 2 and 3) and the group of states with pumping water from the lower to the upper reservoir during minimum load hours (5, 6 and 7). The expressions for state probabilities differ only in one or two terms, which allows an additional and significant simplification of the state probability calculation within those two basic groups of states. These additional relations that facilitate the probability calculations read as follows:

$$P_2 = P_1 \frac{\lambda_G(\rho_+ + \mu_G)}{\mu_G(\rho_+ + \rho_- + \mu_G)},$$
$$P_3 = P_1 \frac{\lambda_G \rho_-}{\mu_G(\rho_+ + \rho_- + \mu_G)},$$
$$P_6 = P_5 \frac{\lambda_P(\delta_+ + \mu_P)}{\mu_P(\delta_+ + \delta_- + \mu_P)},$$
$$P_7 = P_5 \frac{\lambda_P \delta_-}{\mu_P(\delta_+ + \delta_- + \mu_P)}. \qquad (9)$$

3 RIZIK ZBOG NEDOSTATKA DOTOKA I ZALIHA VODE

U okviru programskih sustava za planiranje rada elektroenergetskog sustava za razdoblja od razine dana do razine godine riješen je problem planiranja rada protočnih, akumulacijskih i crpno-akumulacijskih hidroelektrana uvažavajući karakteristike vodotoka na kojima su izgrađene akumulacije i hidroelektrane, odnosno samih akumulacija i hidroelektrana. Posebna pozornost posvećena je radu akumulacijskih hidroelektrana koje omogućuju višegodišnja, sezonska i mjesečna izravnavanja protoka i proizvodnje, odnosno opterećenja. Naravno, uključene su i karakteristike pojedinih vodotoka s obzirom na pojavu vodnih valova. S jedne strane, postoje vodotoci čiji je protok tijekom godine prilično

3 INFLOW DEFICIENCY AND INSUFFICIENT WATER STORAGE RISKS

The problem of operation planning of run-of-river, reservoir and pumped-storage hydro power plants for one-day to one-year periods, with allowance made for the characteristics of the watercourses where the reservoirs or hydro power plants are built, is resolved within the framework of power system operation planning. Special attention is devoted to water-storage hydro power plants that enable flow, generation or load adjustments to be made on monthly, seasonal or multi-annual basis. This, of course, includes the characteristics of streams in view of the occurrence of water waves. On one hand, there are ujednačen, ili se s velikom sigurnošću može predviđati, a jednako tako i počeci vodnih valova. S druge strane, postoje vodotoci čije su oscilacije protoka vrlo visoke i neizvjesne, što njihovo predviđanje čini vrlo nesigurnim kao i rad hidroelektrana s kojima su u vezi.

Kod određivanja rizika nedostatka dotoka polazi se od veličine srednjeg dnevnog protoka Q_d (m^3/s) na mjernom mjestu ili profilu, za koju je kao stohastičku veličinu vezana neizvjesnost pojave. Time je i za proizvodnju hidroelektrana vezana neizvjesnost pojave budući da su one ovisne i o količinama vode, ali i o vremenskom rasporedu dotoka. Obje te komponente ovisne su dalje o nizu utjecaja koji su uključeni i u neizvjesnosti pojava srednjih dnevnih dotoka, koji se dobiju kao rezultat svakodnevnih promatranja i mjerenja. Srednji dnevni dotoci poredani kronološkim redom daju tjedne, mjesečne i godišnje dijagrame protoka na mjernim mjestima ili profilima. Na temelju tih dijagrama određuju se krivulje trajanja protoka, odnosno krivulje vjerojatnosti protoka tjedana, mjeseci ili sezona, te godine.

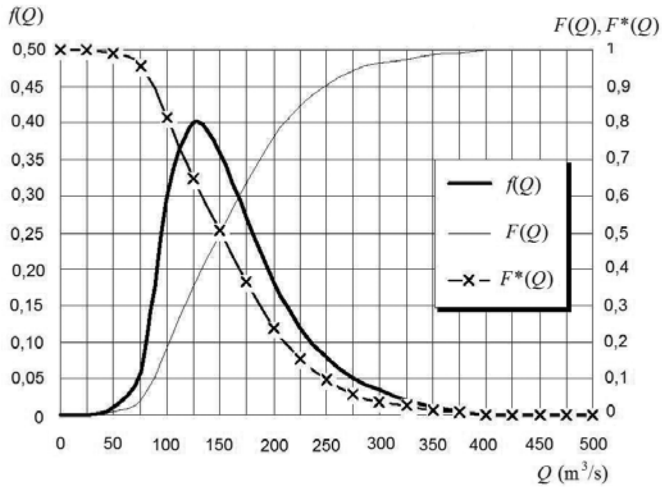
Međutim, za točnije određivanje vjerojatnosti pojave protoka i neizvjesnosti proizvodnje hidroelektrana radi njihova uključivanja u proračun pokazatelja pouzdanosti i raspoloživosti elektroenergetskog sustava nužno je odrediti pripadajuće krivulje vjerojatnosti protoka, i to po kraćim vremenskim razdobljima od jedne godine. Prema tako dobivenim krivuljama zatim se mjere i valoriziraju hidrološki uvjeti, a pripadajuće vjerojatnosti pojave određuju se znatno točnije. Pritom se uvijek mora uzeti u obzir da rad s kraćim vremenskim razdobljima može izazvati iskrivljenja i pogreške kod obrade malih i velikih protoka, a da su veličine iskrivljenja i pogrešaka ovisne o veličinama i učestalostima promjena protoka.

U ovom radu neće se izlagati sam postupak matematičko-stohastičkom obradom, nego će se pretpostaviti da su za mjerna mjesta protoka već na raspolaganju odgovarajuće funkcije gustoće vjerojatnosti $f(Q)$ ili frekvencije pojave protoka, odnosno funkcija distribucije (razdiobe) protoka $F(Q)$ i njen komplement $F^*(Q) = 1 - F(Q)$. Funkcijom distribucije protoka $F(Q)$ određena je vjerojatnost pojave protoka koji je manji ili jednak protoku Q, a njezinim komplementom, tj. funkcijom distribucije $F^*(Q) = 1 - F(Q)$ vjerojatnost pojave protoka većeg od Q (slika 2).

streams with a rather even flow over the year or predictable with a fair amount of certainty, there are also the beginnings of water waves. On the other hand, there are streams with high and unpredictable inflow variations which make their forecasts extremely insecure, and thereby the operational planning of hydro power plants associated with them.

In establishing the inflow deficiency risk the starting point is the average daily inflow value Q_d (m^3/s) at the measuring point or profile, which as a stochastic value involves the uncertainty of event. That is why the output of hydro power plants involves the uncertainty of event, since hydro power plants depend on both the quantities of water inflows and the seasonal inflow pattern. Both of these components are further linked to a series of impacts involved in the uncertainties of average daily inflow, obtained as a result of day-to-day observations and measurements. Average daily inflows lined up chronologically provide weekly, monthly and annual inflow diagrams on the measuring points or profiles. The inflow duration curves are determined on the basis of these diagrams, and so are the weekly, monthly or annual inflow probability curves. However, for more accurate determination of the inflow probability and the uncertainty of hydro power plant generation for their inclusion in the calculation of power system reliability and availability indicators it is necessary to define the pertaining inflow probability curves for periods shorter than a year. The curves thus obtained serve then as a basis for calculating and evaluating the hydrological conditions, whereas the appurtenant probabilities are defined with much greater precision. What must always be taken into account in this procedure is that work with shorter periods of time may lead to distortions and errors in calculations with low and high inflows, whereas the values of these distortions and errors depend on the inflow variation transition values and rates.

This work will not describe the mathematical-stochastic procedure itself, it will be assumed instead that appropriate probability density functions $f(Q)$ or inflow occurrence frequencies or inflow distribution function $F(Q)$ and its complement $F^*(Q) = 1 - F(Q)$ are already available for inflow measuring points and profiles. The inflow distribution function $F(Q)$ defines the inflow probability which is lower than or equal to inflow Q, whereas its complement, i.e., distribution function $F^*(Q) = 1 - F(Q)$ defines inflow probability higher than Q (Figure 2).



Slika 2 – Funkcije $f(Q)$, $F(Q)$ i $F^*(Q)$
Figure 2 – Functions $f(Q)$, $F(Q)$ and $F^*(Q)$

Funkcija distribucije protoka $F(Q)$ ima sljedeći oblik:

The inflow distribution function $F(Q)$ has the following shape:

$$F(Q) = \int_{-\infty}^{Q} f(q)\ \mathrm{d}Q \cong \int_{Q_{\min}}^{Q} f(Q)\ \mathrm{d}Q, \tag{10}$$

gdje je:

$Q_{\min}$ minimalna vrijednost protoka na mjernom mjestu.

Vjerojatnost u krivulji vjerojatnosti protoka može se shvatiti kao relativno trajanje protoka, gdje je ukupno trajanje normirano na jedinicu, čime se dobiva i krivulja trajanja protoka. Njezina je točnost tim veća što je dulji niz godina za koji se raspolaže podacima i što je postupak aproksimacije točniji. Prethodno naznačeni postupak provodi se za vremenske intervale kraće od godine (mjesec ili tjedan), da bi se dobile krivulje vjerojatnosti koje odražavaju periodičke varijacije protoka i njima pridruženih vjerojatnosti tijekom godine.

Ovisno o duljini vremenskog razdoblja, kod elektroenergetskog bilanciranja moguće proizvodnje hidroelektrana određuju se bilo izborom referentne hidrologije, kada se radi o planiranju za dulja razdoblja (mjesec, više mjeseci, godina), bilo predviđanjem protoka, kada se radi o planiranju za kraća razdoblja (dan, tjedan ili par tjedana). Bez obzira na trajanje, za svaki dan tijekom razdoblja planiranja u proračun se ulazi sa zadanim protokom i njemu pridruženom vjerojatnošću ostvarenja, ili s protokom koji odgovara unaprijed odabranoj vjerojatnosti pojave hidroloških uvjeta

where:

$Q_{\min}$ is a minimum inflow value at the measuring point.

The probability in the inflow probability curve can be seen as a relative duration of inflow where the overall duration is standardised to value one, whereby the inflow duration curve is also obtained. Its accuracy rises with the rising number of years for which data are available, and with the rising accuracy of the approximation procedure. The said procedure is carried out for time intervals shorter than a year (a month or a week), so as to obtain probability curves which reflect seasonal inflow variations and related probabilities over the year.

Depending on the length of the period concerned, in the process of power balancing possible outputs of hydro power plants are established either through the choice of reference hydrology, when it comes to longer-term planning (a month, several months, a year), or by inflow forecasting when it comes to shorter-term planning (a day, a week or a couple of weeks). Regardless of the duration, for every day of the planning period calculation is started with a given inflow and its related materialisation probability or with the inflow corresponding to a pre-selected probability of the prema krivulji vjerojatnosti ili trajanja protoka. Pritom se može postupiti na dva načina.

Prvi je, što je više primjereno planiranjima za dulja vremenska razdoblja, kada se protoci, a time i moguće proizvodnje i opterećenja, određuju prema odabranoj hidrologiji koja u pravilu ima veću vjerojatnost ostvarenja. Odabrana hidrologija predstavlja odrednicu za simulaciju rada sustava, jer se kod proračuna pouzdanosti i raspoloživosti sustava proizvodnja i opterećenje hidroelektrane prema odabranom modelu uključuju u dijagram opterećenja, a hoće li izvršiti namijenjenu ulogu, ovisi o odnosu prema slučajno odabranom broju koji je uniformno distribuiran na intervalu (0,1).

Hidroelektrana će izvršiti namijenjenu ulogu u svim onim slučajevima kada slučajno odabrani broj u krivulji vjerojatnosti protoka pada u područje vjerojatnosti protoka većih od protoka prema unaprijed određenoj ili zadanoj hidrologiji. I obrnuto, hidroelektrana neće moći izvršiti namijenjenu ulogu ako generirani broj u krivulji vjerojatnosti protoka pada u područje vjerojatnosti protoka manjih od protoka prema unaprijed određenoj ili zadanoj hidrologiji. U oba prethodna slučaja u osnovi se promatra odgovarajući komplement funkcije distribucije. Rizik nedostatka vode kao mjera neizvjesnosti proizvodnje i opterećenja hidroelektrane simulacijom se uključuje u proračune pouzdanosti sustava.

Drugi je način da se prije elektroenergetskog bilanciranja simulacijom, metodom generiranja slučajnih brojeva prema krivulji vjerojatnosti protoka odredi niz protoka, a to znači i njima pridružene moguće proizvodnje i opterećenja hidroelektrane. U tom slučaju rizik nedostatka vode kao mjera neizvjesnosti proizvodnje hidroelektrane uključuje se već na samom početku proračuna pokazatelja pouzdanosti i raspoloživosti. Pritom se podrazumijeva da će točnost postupka rasti s brojem simulacija, što je u slučaju primjene značajka Monte Carlo metode simulacije [5], [9] i [10].

Kod hidroelektrana koje vode koriste kako dotječu i koje zbog ograničenog kapaciteta kompenzacijskih bazena nisu u mogućnosti akumulirati veće količine vode, rizik nedostatka zaliha vode može se zanemariti budući da nema gotovo nikakvu važnost. Pogotovo to vrijedi u usporedbi s akumulacijskim hidroelektranama. Relativna važnost rizika nedostatka dotoka raste s podizanjem tehničke spremnosti postrojenja da što bolje iskoristi raspoložive količine vode budući da u tom slučaju moguće proizvodnje i opterećenja ovise samo o raspoloživim količinama vode iz dotoka.

occurrence of hydrological events according to the probability curve or inflow duration. The matter can be approached in two ways.

The first approach, which is more appropriate for longer-term planning, is applied where the inflows and thereby possible outputs and loads are defined according to the selected hydrology which as a rule is more likely to materialise. The selected hydrology is a guideline for system operation simulation, because in the system reliability and availability calculation the output and load of a hydro power plant are included in the load diagram according to the selected model, whereas whether or not its performance will meet expectations depends on a randomly selected number which is evenly distributed on the interval (0,1).

The hydro power plant will play its assigned role in all cases when the randomly selected number in the inflow probability curve falls into the area of inflow probabilities higher than inflows in the predetermined or pre-given hydrology. Vice versa, the hydro power plant will be unable to play its assigned role if the number generated in the inflow probability curve falls into the area of inflow probability lower than the inflows in the predetermined or pre-given hydrology. In both of these cases, what is basically observed is the corresponding distribution function complement. The water deficiency risk as a measure of the plant's output and load uncertainty is included through simulation in the system reliability calculation.

The second approach is that before the power balance simulation the sequence of inflows is determined by the method of generating random numbers based on the inflow probability curve, and thereby the plant's possible outputs and loads associated with them. In that case the water deficiency risk, as a measure of output uncertainty, is included at the very beginning of calculating the reliability and availability indicators. In this regard it is understood that that the accuracy of the procedure will grow with the number of simulations, which is a feature of the Monte Carlo simulation method [5], [9] and [10].

With hydro power plants using inflows as they come and those which cannot accumulate larger amounts of water due to limited capacities of compensation reservoirs, the water deficiency risk can be disregarded as it is of no importance. This particularly applies in respect of storage plants. The relative importance of the inflow deficiency risk grows with the improving capability of the plant to make optimum use of available water, because in that case potential outputs and loads solely depend on available water inflows.

4 UTJECAJ RIZIKA NEDOSTATKA DOTOKA NA RAD CRPNO-AKUMULACIJSKE HIDROELEKTRANE

Rad crpno-akumulacijske hidroelektrane u slučaju da je prirodni dotok u gornji akumulacijski bazen jednak ili veći od potrebnog za rad u razdoblju vršnih opterećenja ili za pokrivanje potreba za brzim startom ne razlikuje se od rada bilo koje druge akumulacijske hidroelektrane. Međutim, u slučaju da prirodnog dotoka u gornji akumulacijski bazen uopće nema, ili je pak nedovoljan za pretpostavljeni način rada, pojavljuje se potreba za crpljenjem vode iz donjeg akumulacijskog bazena u gornji.

Daljnja razmatranja znatno se olakšavaju ako se uvedu sljedeće tri pretpostavke. Prva je da u donjem bazenu, tj. na usisnoj strani u svakom trenutku stoje na raspolaganju dovoljne količine vode za crpljenje. U protivnom, neizvjesnost pojave dotoka i stanja donjeg akumulacijskog bazena mora se uključiti u ukupnu neizvjesnost ili rizik nedostatka vode. Druga je pretpostavka da se voda crpi u razdobljima malih opterećenja sustava, čime se želi izbjeći isključivanje iz pogona agregata u termoelektranama tijekom noći ili preko vikenda, ili kada je na bilo koji drugi način na raspolaganju jeftina energija za crpljenje. Treća pretpostavka vrijedi za slučaj pojave potrebe za brzim startom, a podrazumijeva sposobnost vrlo brzog prelaska iz stanja crpljenja punim opterećenjem u turbinski pogon punim opterećenjem. Kada je u pogonu, crpno-akumulacijska hidroelektrana treba proizvoditi uz maksimalno moguću snagu. Rad crpno-akumulacijske hidroelektrane planira se u ciklusima, najčešće tjednim, a način uključivanja u dijagram opterećenja prikazan je na slici 3.

Potrebu za crpljenjem određuju prirodni dotoci u gornji akumulacijski bazen i potrebna proizvodnja. Ako prirodnog dotoka nema, odnos energije crpljenja $E_{p,h}$ i proizvedene energije $E_{g,h}$ određen je izrazom:

4 THE IMPACT OF INFLOW DEFICIENCY RISK ON THE OPERATION OF PUMPED-STORAGE HYDRO POWER PLANTS

The operation of a pumped-storage hydro power plant in cases where the natural inflow into the upper storage reservoir equals or exceeds the operational requirements in peak load periods or the quick-start requirements does not differ from the operation of any other storage hydro power plant. However, in case of complete absence of natural inflow into the upper reservoir or if it does not suffice for the required operation regime, a need appears to pump water from the lower to the upper reservoir.

Further considerations will be much easier if the following three conditions are introduced. The first is that in the lower reservoir, i.e., on the suction side a sufficient amount of water for pumping is available at any time. Otherwise the uncertainty of inflow and the level of the lower reservoir must be included in the overall uncertainty or the water deficiency risk. The second condition is that water is pumped during low load periods, in order to avoid a shut-down of generator units in thermal power plants during the night or over weekends, or in situations when cheap pumping power is available from any other source. The third condition applies if there is a need for an instantaneous start and it implies a possibility of very rapid transition from full-load pumping operation to full-load turbine drive. When in operation, the pumped-storage hydro power plant should generate at maximum capacity. The operation of a pumped-storage hydro power plant is planned in cycles, mostly on a weekly basis. The way of its inclusion in the load diagram is shown in Figure 3.

Pumping requirements are determined by inflows into the upper reservoir and by the required output. In absence of the inflow, the relation of pumping power $E_{p,h}$ and generated energy $E_{g,h}$ is defined by the following expression:

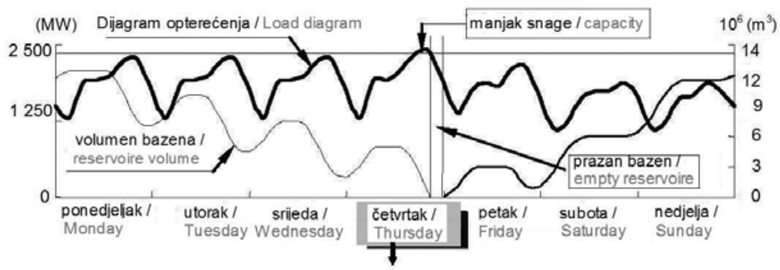
$$E_{g,h} = \eta_h \cdot E_{p,h} \, , \tag{11}$$

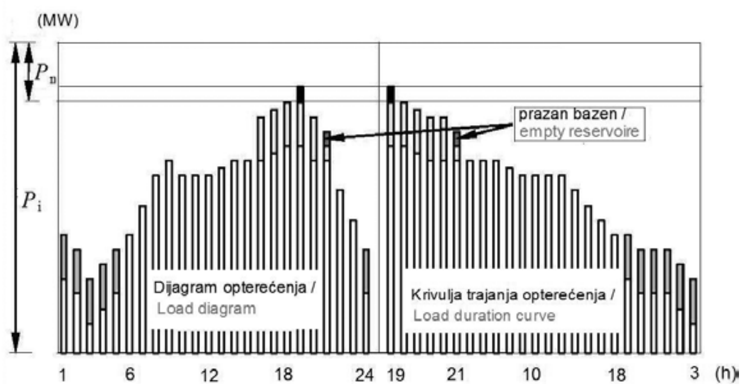
gdje je:

$\eta_h = \eta_{p,h} \cdot \eta_{g,h}$ – stupanj korisnog djelovanja cilusa,
$\eta_{p,h}$ – stupanj korisnog djelovanja crpljenja,
$\eta_{g,h}$ – stupanj korisnog djelovanja proizvodnje električne energije.

where:

$\eta_h = \eta_{p,h} \cdot \eta_{g,h}$ – cycle efficiency rate,
$\eta_{p,h}$ – pumping efficiency rate,
$\eta_{g,h}$ – power generation rate.

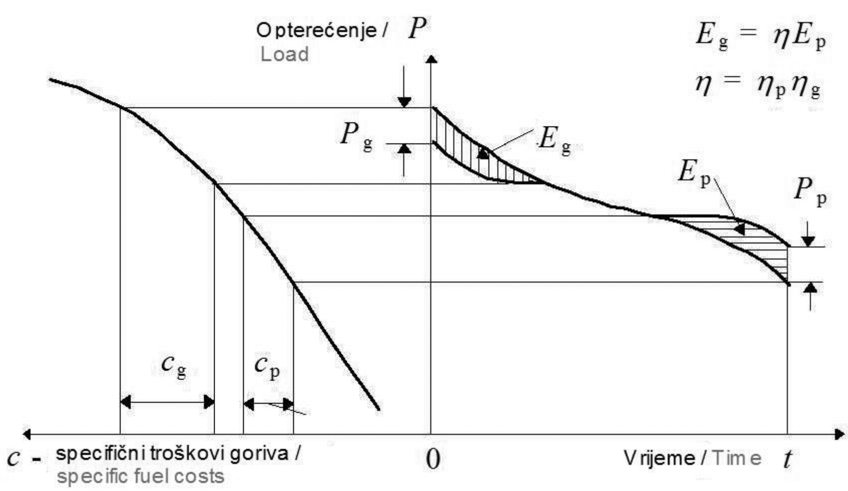




Slika 3 – Uključivanje crpno-akumulacijske hidroelektrane u dijagram opterećenja
Figure 3 – Inclusion of pumped-storage hydro power plant in the load diagram

Energiju za crpljenje osiguravaju termoelektrane sustava nižih specifičnih troškova goriva. Proizvedena snaga crpno-akumulacijske hidroelektrane smješta se u sam vrh dijagrama opterećenja, da bi se proizvedenom energijom smanjila proizvodnja termoelektrana s višim specifičnim troškovima za gorivo (slika 4).

The pumping power is provided by thermal power plants with lower specific fuel costs. The generated power of a pumped-storage hydro power plant is placed on the very top of the load curve, so as to reduce the output of thermal power plants with higher specific fuel costs (Figure 4).



Slika 4 – Smještaj crpno-akumulacijske hidroelektrane u dijagramu opterećenja
Figure 4 – Location of the pumped-storage hydro power plant in the load diagram

Ekonomičan rad ostvaruje se ako je ispunjen uvjet:

Economical operation is achieved if the following condition is met:

$$c_p E_{p,h} \le c_g E_{g,h} , \quad (12)$$

odnosno:

or:

$$c_p \le c_g \ \eta , \quad (13)$$

gdje je:

c_p - specifični troškovi goriva termoelektrana koje proizvode energiju za crpljenje,
c_g - specifični troškovi goriva termoelektrana čija se proizvodnja smanjuje proizvodnjom crpnoakumulacijske hidroelektrane.

Dakle, ekonomičan rad postiže se kada je povećana štednja promjenjivih pogonskih troškova, dobivena neopterećivanjem termoelektrana u vršnom dijelu krivulje trajanja opterećenja, jednaka ili veća od povećanih promjenjivih pogonskih troškova crpljenja, uzimajući pritom u obzir korisnost ciklusa. Time se uvjet (13) može napisati i u obliku:

where:

c_p - specific fuel costs in thermal power plants which provide power for pumping;
c_g - specific fuel costs in thermal power plants whose output is diminishing through the output of pumped-storage hydro power plants.

Therefore, economical operation is achieved when the increased savings in variable fuel costs, obtained through reduced capacity of thermal power plants in the peak section of the load curve, equals or exceed the increased variable pumping costs, taking into account the cycle efficiency. Thus the condition (13) can also be expressed as follows:

$$\Delta c_p \le \eta \cdot \Delta c_g \ . \quad (14)$$

Rizik nedostatka vode javlja se zbog mogućnosti pojave nedovoljnog prirodnog dotoka, kao i nedostatka kapaciteta, tj. snage i energije za crpljenje. Tu treba uključiti i slučaj potrebe da se prekine crpljenje radi brzog pokrivanja iznenadnih manjkova snage u sustavu.

Osnovni model za uključivanje crpno-akumulacijske hidroelektrane u model pouzdanosti elektroenergetskog sustava jest model vršne jedinice kojoj se u učestalosti kvarova pri startu, koji znače nemogućnost preuzimanja opterećenja, i učestalosti kvarova tijekom pogona, uključuju rizici nedostatka vode. Zbog vrlo male učestalosti kvarova takvih postrojenja, moguća je i potpuna zamjena učestalosti kvarova učestalostima pojave nedostatka vode. Pritom se u razmatranja moraju uključiti kriteriji rada koji mogu biti samo ekonomski, samo sigurnosni, ili kombinacija obaju.

Čisto ekonomski pristup moguć je kada u sustavu postoje raspoloživi i drugi kapaciteti koji mogu preuzeti opterećenje prema kriteriju ekonomičnosti. Kriteriji ekonomičnosti navedeni su ranije.

There is a water deficiency risk due to the possibility of inflow deficiency, as well as due to the lack of capacity, i.e., capacity and power required for pumping. Another contingency to be taken into account is a sudden need to discontinue the pumping operation in order to make up quickly for sudden power shortages in the system.

The basic model for the inclusion of pumped-storage hydro power plants in the power system reliability and availability model is the peak unit model to which water deficiency risks are added in the transition rate of start operation incurred failures, resulting in the inability to take over the load, and in the transition rate of drive operation incurred failures. Owing to a very low failure transition rate in such plants, it is possible to wholly replace the failure transition rate by the water deficiency transition rate. In such considerations operation criteria must be included which may be exclusively economic or exclusively safety-related, or a combination of both.

A purely economic approach is possible when there are other capacities available in the system that can take over the load in accordance with the criteria

Čisto sigurnosni pristup najčešće je vezan za slučajeve kada je sveukupni raspoloživi kapacitet sustava nizak, te se, bez obzira na troškove, traži cjelokupni kapacitet crpno-akumulacijske hidroelektrane. Razlog je za to potreba da se pokrije što veći iznos nedostajućeg opterećenja. Crpno-akumulacijska hidroelektrana zauzima posljednje mjesto u listi prioriteta kako bi se voda držala raspoloživom koliko god je to moguće. S druge strane, voda se koristi do potpunog pražnjenja gornjeg bazena, kada se manjak snage u sustavu povećava za cjelokupnu snagu hidroelektrane. Ponovno punjenje gornjeg bazena vrši se opterećenjem prve raspoložive termoelektrane bez obzira na njezin tip ili specifične troškove proizvodnje. Time se izazivaju visoki dodatni troškovi u sustavu.

Treći slučaj kombinacija je prethodna dva, a u osnovi predstavlja nastojanje da se smanje troškovi u sustavu i da se izbjegne potpuni gubitak kapaciteta crpno-akumulacijske hidroelektrane. To se postiže planiranjem rada prilagođenog zahtjevima svakog pojedinog pogonskog slučaja. Za isti ukupni iznos neisporučene energije preraspodjelom nepokrivenog opterećenja tijekom sati vršnog opterećenja dobije se niz stanja kada potrebe sustava nisu u potpunosti pokrivene, ali su njihove amplitude i trajanja puno niža, što je i prihvatljivije za sustav. Pokraj toga, smanjuje se i proizvodnja termoelektrana s najvišim proizvodnim troškovima, a isto tako i broj potpunih pražnjenja gornjeg bazena. Potpunim pražnjenjem gornjeg bazena gubi se mogućnost pokrivanja dinamičkih obveza kao što su rotirajuća ili pripravna rezerva, regulacija snage i frekvencije. Takve obveze utječu na nastanak rizika nedostatka vode, ali na bitno različit način. Naime, kod rotirajuće rezerve ili brzog starta trošenje vode znatno je smanjeno ili traje vrlo kratko, za razliku od regulacije koja traži kontinuiran pogon tijekom dužeg razdoblja i znatniji utrošak vode. U tom drugom slučaju, da bi se smanjio rizik nedostatka vode koji se pojavljuje zbog znatnijih pražnjenja, prelazi se na pristup koji znači veće troškove u sustavu.

Kada se odredi osnovni pristup planiranju, tj. pogonu crpno-akumulacijske hidroelektrane, ostaje još odrediti osnovne parametre modela za simulacijski postupak proračuna pouzdanosti. Ti su parametri u prvom redu ovisni o postojanju prirodnog dotoka, a to znači o njegovom stohastičkom karakteru. Kada u gornji bazen dotječe dovoljno vode iz prirodnog dotoka, pogon se tretira kao pogon akumulacijske hidroelektrane. Međutim, kada tog dotoka nema ili nije dovoljan, ukupna proizvodnja crpno-akumulacijske hidroelektrane neovisna je o promjenjivim količinama vode iz dotoka, što ne vrijedi i za energiju crpljenja vode u gornji bazen

of economic feasibility. The economic criteria were mentioned earlier.

A purely safety-motivated approach is mostly associated with the cases where the overall available capacity of the system is low, so that, regardless of costs, the total capacity of a pumped-storage hydro power plant is sought. The reason for it is the need to cover the greatest possible amount of the missing load. Pumped-storage hydro power plants are placed at the bottom of the priority list in order to keep water available as long as possible. On the other hand, water is used up to the total discharge of the upper reservoir when power shortage in the system is increased by the hydro plant's total power. Refilling of the upper reservoir is done by loading the first thermal power plant available regardless of its type or specific generation costs. This involves high extra costs in the system.

The third case is a combination of the above mentioned two cases and is basically an attempt to reduce system costs and to avoid a complete loss of capacity of the pumped-storage hydro power plant. That can be achieved with operation planning adapted to the requirements of each particular operation case. For the same total amount of undelivered energy, through redistribution of uncovered load during the peak load hours a series of states are obtained where the system needs are not fully met, but their amplitudes and duration are much lower, which is more acceptable for the system. In addition, the output of thermal power plants with the highest generation costs is decreased, and so is the number of upper reservoir depletions. Upon complete depletion of the upper reservoir the possibility is lost to cover dynamic obligations such as the spinning reserve or stand-by reserve, capacity and frequency regulation. Such obligations have an impact on the occurrence of water deficiency risk, but in an entirely different way. Namely, in using the spinning reserve or the instantaneous start water consumption is much lower or takes a very short time, unlike the regulation which requires continuous operation over a longer period of time and more water consumption. In the latter case, in order to lower the water deficiency risk resulting from significant discharges the approach is taken which involves higher system costs.

Once the basic approach to planning, i.e., to the pumped-storage hydro power plant operation has been defined, what still remains to be defined are the basic parameters of the reliability calculation simulation model. These parameters depend in the first place on the natural inflow, in other words, on its stochastic character. When enough water flows into the upper reservoir from the natural inflow, the drive is treated as a drive of the storage hydro power plant. However, in absence of that inflow, or if it is insufficient, the total output of the pumped-storage hydro power plant is independent of the variable quantities koju trebaju osigurati ostale elektrane u sustavu. Za tu energiju vrijedi razdioba vjerojatnosti uvjetovana prirodnim dotokom.

Maksimalna snaga crpno-akumulacijske hidroelektrane u generatorskom pogonu iznosi:

of inflow water, which does not apply to the energy of water pumping into the upper reservoir to be provided by other power plants in the system. What applies to this energy is probability distribution determined by the natural inflow.

Maximum capacity of a pumped-storage hydro power plant in the generator operation mode is:

$$P_{g,max} = 9{,}81\ Q_A \cdot H_n \cdot \eta_t \cdot 10^{-3}\ [\mathrm{MW}], \qquad (15)$$

gdje je:

H_n – neto pad [m],
$H_p = \alpha \cdot H_b$,
H_b – bruto pad [m],
α – omjer neto i bruto pada,
η_t – stupanj korisnog djelovanja u turbinskom pogonu.

Snaga crpljenja potrebna za maksimalni protok crpljenja $Q_{p,max}$ iznosi:

where:

H_n – net fall [m],
$H_p = \alpha \cdot H_b$,
H_b – gross fall [m],
α – net-gross fall ratio,
η_t – efficiency rate in turbine drive.

Pumping capacity required for maximum pump flow $Q_{p,max}$ is:

$$P_{p,max} = 9{,}81 \cdot Q_{p,max} \cdot H_b \frac{1}{\eta_p} 10^{-3}\ [\mathrm{MW}], \qquad (16)$$

gdje je:

$Q_{p,max}$ – maksimalni protok crpki [m^3/s],
η_p – stupanj korisnog djelovanja u crpnom pogonu.

Budući da se rad crpno-akumulacijske hidroelektrane u osnovi planira u tjednim ciklusima, tjedni iznos energije koja se bez prirodnog dotoka može proizvesti maksimalnom snagom u turbinskom pogonu iznosi:

where:

$Q_{p,max}$ – maximum pump flow [m^3/s],
η_p – efficiency rate in pump operation mode.

As the operation of a pumped-storage hydro power plant is planned in weekly cycles, the weekly amount of power that can be generated without natural inflow at maximum capacity in turbine drive is:

$$W_{vt,max} = P_{g,max}\ r\ t_{vt} \cdot 10^{-3}\ [\mathrm{GWh}], \qquad (17)$$

gdje je:

r – broj radnih dana u tjednu,
t_{vt} – maksimalno moguće trajanje korištenja mak simalne snage u turbinskom pogonu, bez obzira na eventualnu dodatnu proizvodnju iz prirodnog dotoka.

Energiju za crpljenje osiguravaju ostale elektrane sustava, i to u razdoblju malih opterećenja čije trajanje određuje sljedeći izraz:

where:

r – working days in a week,
t_{vt} – maximum possible duration of using maximum capacity in turbine drive regardless of possible additional generation from natural inflow

Power for pumping is provided from other plants in the system in low-load periods, the duration of which is defined by the following expression:

$$T_m = T - r\,t_v = 24(r+n) - r\,t_v\,, \quad (18)$$

gdje je:

T – trajanje ciklusa (168 sati za tjedan),
n – broj neradnih dana u ciklusu,
t_v – trajanje vršnih opterećenja u radnom danu.

U slučaju da nema prirodnog dotoka, količina vode koja se traži u turbinskom pogonu mora biti jednaka količini vode koja je crpljenjem dovedena u gornji bazen, tako da je maksimalni protok crpki određen izrazom:

where:

T – cycle duration (168 hours per week),
n – number of non-working days in a cycle,
t_v – peak load duration on a working day

In absence of natural inflow, the amount of water required in turbine drive must be equal to the amount of water brought by pumping to the upper reservoir, so that maximum pump flow is defined by the expression:

$$Q_{p,max} = Q_A \frac{r\,t_{vt}}{24(r+n) - r\,t_v}\,, \quad (19)$$

gdje je:

Q_A – maksimalni protok turbina (veličina izgradnje) [m^3/s],

To znači da su veličine $Q_{p,max}$ i $P_{p,max}$ ovisne o obliku dijagrama opterećenja, odnosno o načinu rada hidroelektrane. Tjedna količina energije potrebna za crpljenje vode u gornji bazen iznosi:

where:

Q_A – maximum turbine flow (designed size) [m^3/s],

This means that the values $Q_{p,max}$ and $P_{p,max}$ are determined by the shape of the load diagram, i.e., the hydro power plant's operation mode. The weekly amount of power required for water pumping into the upper reservoir is:

$$W_{p,max} = P_{p,max}\,T_m 10^{-3} = 9{,}81\;Q_A H_b \frac{1}{\eta_p} r\,t_v 10^{-6}\;[\mathrm{GWh}]. \quad (20)$$

Pomoću izraza (16) dobije se:

With expression (16) the following is obtained:

$$W_{p,max} = \frac{P_{g,max}\;r\,t_{vt} 10^{-3}}{\eta_t\,\eta_p\,\alpha} = \frac{W_{vt,max}}{\eta_t\,\eta_p\,\alpha}\;[\mathrm{GWh}]. \quad (21)$$

Ako postoji prirodni dotok u gornji bazen, on će se nastojati iskoristiti uz maksimalnu snagu hidroelektrane, a trajanje takvog rada određuje se iz uvjeta jednakosti količine vode koja dotječe tijekom ciklusa (tjedna) i količine vode kojom se proizvodi energija uz maksimalni protok. Dakle:

If there is a natural inflow into the upper reservoir, an attempt will be made to use it at maximum capacity of the hydro power plant, and the duration of such operation will be determined based on the equal amount of water coming in during a cycle (week) and the amount of water used for generating electricity at maximum flow. Hence:

$$t_{va} = \frac{24(r+n)Q}{r\,Q_A}\,. \quad (22)$$

Tijekom t_{vt} sati proizvodi se energija dijelom iz prirodnog dotoka, a dijelom crpljenjem vode u gornji akumulacijski bazen. Kada je $t_{va} < t_{vt}$, crpljenje je potrebno u trajanju $t_{vt} - t_{va}$ sati, i to za proizvodnju maksimalnom snagom. Iz prirodnog dotoka proizvodi se energija:

During t_{vt} hours electricity is generated partly from the natural inflow and partly by pumping water into the upper reservoir. When $t_{va} < t_{vt}$, the required duration of pumping is $t_{vt} - t_{va}$ hours, at full capacity. Electricity generated from natural inflow amounts to:

$$W_{va} = P_{g,max}\ r\ t_{va} 10^{-3}\ [\mathrm{GWh}], \qquad (23)$$

a iz vode koja je crpljena:

and electricity from pumped water:

$$W_{pa} = P_{g,max}\ r\ (t_{vt} - t_{va}) 10^{-3} = W_{vt,max} - W_{va}\ [\mathrm{GWh}]. \qquad (24)$$

Protok crpki je:

The pump flow is:

$$Q_p = Q_A \frac{r(t_{vt} - t_{va})}{24(r+n) - r\ t_v}. \qquad (25)$$

Za taj protok potrebna je snaga crpki:

This flow requires the following pump capacity:

$$P_p = 9{,}81\ Q_p\ H_b \frac{1}{\eta_p} 10^{-3}\ [\mathrm{MW}]. \qquad (26)$$

Iz prethodnog slijedi ovisnost snage crpki o prirodnom dotoku:

Dependence of pump capacity on the natural inflow can be derived from the foregoing:

$$P_p = \frac{9{,}81\ H_b\ Q_A\ r\ t_{vt} 10^{-3}}{\eta_p [24(r+n) - r\ t_v]\alpha} - \frac{9{,}81\ H_b 24(r+n) 10^{-3}}{\eta_p [24(r+n) - r\ t_v]\alpha} Q$$
$$= \frac{P_{g,max}\ r\ t_{vt}}{\eta_t\ \eta_p\ T_m\ \alpha} - \frac{P_{g,max}\ 24(r+n)}{Q_A\ \eta_t\ \eta_p\ T_m\ \alpha} Q \quad [\mathrm{MW}]. \qquad (27)$$

Za pretpostavljene konstantne bruto padove i stupnjeve korisnog djelovanja ta ovisnost je linearna i može se napisati u obliku:

For the assumed constant gross falls and efficiency rates the said dependence is linear and can be expressed as follows:

$$P_p = C_1 - C_2\ Q\ [\mathrm{MW}], \qquad (28)$$

gdje su :

C_1, C_2 – parametri ovisnosti snage crpki pumpno-akumulacijske hidroelektrane o prirodnom dotoku.

where:

C_1, C_2 – parameters of pump capacity dependence on natural inflow.

Funkcija $P_p = f(Q)$ prikazana je na slici 5. Za više crpki radi se o familiji krivulja. Konstantni dio krivulje nastaje kao posljedica toga što je za slučaj $i < n$ i crpki u pogonu, te protok $Q \le Q_t^{(i)}$ na raspolaganju samo snaga $P_{Mp,i}$ kojom se dodatno crpi voda da bi se postigla zahtijevana proizvodnja $W_{vt,max}$. Potrebna energija za crpljenje iznosi:

Function $P_p = f(Q)$ is shown in Figure 5. More pumps make a family of curves. The constant section of the curve is a result of the fact that for the case $i < n$ pumps in operation, and the flow $Q \le Q_t^{(i)}$ only $P_{Mp,i}$ capacity is available used for additional water pumping so as to achieve the required output $W_{vt,max}$. Power required for pumping is:

$$W_{pm} = P_p\, T_m\, 10^{-3} = 9{,}81\, Q_A\, H_b \frac{1}{\eta_p} r\ (t_{vt} - t_{va}) 10^{-6}$$
$$= \frac{P_{g,max}\, r\ (t_{vt} - t_{va}) 10^{-3}}{\eta_t\, \eta_p\, \alpha} = \frac{1}{\eta_t\, \eta_p\, \alpha} (W_{vt,max} - W_{va}) \quad [\text{GWh}]. \qquad (29)$$

Ako je prirodni dotok u gornji akumulacijski bazen takav da omogućava korištenje maksimalne snage i duže od vremena t_{vt}, $t_{va} > t_{vt}$, crpljenje nije potrebno.

Nakon što je određena ukupna potrebna proizvodnja crpno-akumulacijske hidroelektrane $W_{vt,max}$, neizvjesnost pojave dotoka u gornji bazen zapravo ima utjecaja samo na potrebnu energiju crpljenja koju osiguravaju ostale elektrane sustava. Za tu energiju može se uzeti da ima prirodnim dotokom uvjetovanu razdiobu vjerojatnosti. Energiju za crpljenje proizvode ostale elektrane sustava, i to tijekom razdoblja minimalnih opterećenja, zbog čega dijagram opterećenja sustava raste za iznos ispadima uvjetovane snage crpljenja. Time se modificira dijagram opterećenja, što znači da model opterećenja treba prilagoditi novonastaloj situaciji.

Razdioba vjerojatnosti prirodnog dotoka ranije je detaljno obrađena. Moguća proizvodnja računa se prema izrazu:

If the natural inflow into the upper reservoir suffices to allow the use of maximum capacity for periods longer than t_{vt}, $t_{va} > t_{vt}$, no pumping will be necessary.

After determining the total required output of the pumped-storage hydro power plant, $W_{vt,max}$, the uncertainty of inflow into the upper reservoir has an impact only on power required for pumping provided from other plants within the system. It can be assumed that power has a probability distribution determined by the natural inflow. It can be assumed that this power has a probability distribution determined by natural inflows. Power for pumping is generated by other plants in the system during the periods of minimum load. For that reason the system load diagram is rising by the amount of outage-determined pumping capacity. The load diagram is thereby modified, which means the load model should be adjusted to the newly arisen situation.

The natural inflow probability distribution has already been described above in detail. Possible output is calculated by means of the following expression:

$$W_{va} = \frac{W_{vt,max}}{Q_A} Q\ [\text{GWh}]. \qquad (30)$$

Iz razdiobe vjerojatnosti prirodnog dotoka i ovisnosti (30) formira se funkcija gustoće vjerojatnosti $f(W_{va})$, tj. funkcije gustoće vjerojatnosti proizvodnje crpno-akumulacijske hidroelektrane isključivo koristeći prirodni dotok. Vjerojatnost da se ta proizvodnja nalazi u intervalu $[W'_{va},\ W'_{va} + \Delta W_{va}]$ jednaka je vjerojatnosti pojave dotoka iz intervala $[Q',\ Q' + \Delta Q]$, dakle:

From the natural inflow probability distribution and dependency (30) the probability density function $f(W_{va})$ is formed, i.e., the probability density function of the output of the pumped-storage hydro power plant by using the natural inflow only. The probability that such generation is situated in the interval $[W'_{va},\ W'_{va} + \Delta W_{va}]$ equals the probability of inflow from the interval $[Q',\ Q' + \Delta Q]$, hence:

$$[P(Q' < Q \le Q' + \Delta Q \approx f(Q)\Delta Q] =$$
$$[P(W'_{va} < W_{va} \le W'_{va} + \Delta W_{va}) \approx f(W_{va})\Delta W_{va}], \qquad (31)$$

Funkcija gustoće proizvodnje hidroelektrane iz prirodnog dotoka ima oblik:

The density function of pumped-storage hydro power plant generation from the natural inflow is shaped as follows:

$$f(W_{va}) = \frac{f(Q)\Delta Q}{\Delta W_{va}} \approx \frac{P(Q' < Q \leq Q' + \Delta Q)}{\Delta W_{va}} \quad . \tag{32}$$

Dotok Q_t za proizvodnju energije $W_{vt,max}$ tijekom sati t_{vt} računa se pomoću izraza:

Inflow Q_t for output $W_{vt,max}$ over t_{vt} hours is calculated by means of the following expression:

$$Q_t = Q_A \frac{W_{vt,max}}{P_{g,max}\, 24(r+n)10^{-3}} = Q_A \frac{r\ t_{vt}}{24(r+n)} \quad . \qquad [m^3/s]. \tag{33}$$

Funkcija gustoće vjerojatnosti proizvodnje crpno-akumulacijske hidroelektrane iz vode koja je crpljenjem dovedena u gornji bazen određuje se iz jednakosti vjerojatnosti energija koje povezuju izrazi (23) i (24). Ta jednakost ima oblik:

The probability density function of pumped-storage hydro power plant generation from water pumped into the upper reservoir is determined from the probability equality of powers linked by expressions (23) and (24). That equality has the following form:

$$\begin{aligned}&\left[P(W'_{va} < W_{va} \leq W'_{va} + \Delta W_{va}) \approx f(W_{va})\Delta W_{va}\right] \\ &= \left[P(W'_{pa} < W_{pa} \leq W'_{pa} + \Delta W_{pa}) \approx f(W_{pa})\Delta W_{pa}\right].\end{aligned} \tag{34}$$

Funkcija gustoće vjerojatnosti energije dobivene crpljenjem vode u gornji bazen sada glasi:

The probability density function of power obtained by pumping water into the upper reservoir now reads as follows:

$$f(W_{pa}) = \frac{f(W_{va})\Delta W_{va}}{\Delta W_{pa}} \approx \frac{P(W'_{va} < W_{va} \leq W'_{va} + \Delta W_{va})}{\Delta W_{pa}} \quad . \tag{35}$$

Potrebno je odrediti i odgovarajuće funkcije potrebne energije crpljenja $f(W_{pm})$. Ovisnost potrebne energije za crpljenje o energiji iz prirodnog dotoka određuje izraz (29). Prema tom izrazu, razlika u odnosu na proizvedenu energiju korištenjem crpljene vode samo je u konstantnom faktoru, odnosno koeficijentu smjera različitom od jedinice, tako da vrijede slična razmatranja. Dakle, prethodni izrazi za vjerojatnost i funkciju gustoće vjerojatnosti mogu se pisati i u obliku:

It is also necessary to determine the corresponding functions of required pumping energy $f(W_{pm})$. The dependence of the required pumping power on natural inflow energy is defined by expression (29). According to it, the difference in relation to power generated by using the pumped water lies only in the constant factor, in other words, in a direction coefficient other than one, so that similar considerations apply. Therefore, the foregoing expressions for probability and for the probability density function can also be expressed as follows:

$$\begin{aligned}&\left[P(W'_{va} < W_{va} \leq W'_{va} + \Delta W_{va}) \approx f(W_{va})\Delta W_{va}\right] \\ &= \left[P(W'_{pm} < W_{pm} \leq W'_{pm} + \Delta W_{pm}) \approx f(W_{pm})\Delta W_{pm}\right],\end{aligned} \tag{36}$$

$$f(W_{pm}) = \frac{f(W_{va})\Delta W_{va}}{\Delta W_{pm}} \approx \frac{P(W'_{va} < W_{va} \leq W'_{va} + \Delta W_{va})}{\Delta W_{pm}} \quad . \tag{37}$$

Potrebna snaga crpljenja crpno-akumulacijske hidroelektrane kad postoji prirodni dotok u gornji akumulacijski bazen ovisi o količini vode koja dotječe, ali i o ispadima uvjetovanoj raspoloživoj snazi crpki. Podloge za razmatranja ispadima su uvjetovana raspoloživa snaga za crpljenje određena na temelju vjerojatnosti ispada crpki prema osnovnom modelu jedinica za crpno-akumulacijski pogon i razdioba vjerojatnosti dotoka. Budući da se cijela hidroelektrana tretira kao komponenta sustava, a da se u pravilu sastoji od više agregata iste snage P_0, diskretna funkcija gustoće $f_p(P_p)$ bit će višestupanjska. Raspoloživa snaga hidroelektrane za crpljenje, uvjetovana ispadima agregata distribuirana je po binomnoj razdiobi.

Raspoloživa snaga crpljenja ima diskretnu funkciju gustoće vjerojatnosti, koja primjenom Diracove funkcije poprima oblik:

The required pump capacity of a pumped-storage hydro power plant, given a natural inflow into the upper reservoir, depends on the amount of incoming water but also on the available outage-determined pump capacity. Considerations are based on the outage-determined available pump capacity determined on the basis of pump outage probability according to the basic pumped-storage unit model and the inflow probability distribution. Given the fact that the whole hydro power plant is treated as a component of the system and that, as a rule, it consists of a number of generating units of the same capacity P_0, the discrete density function $f_p(P_p)$ will be a multi-stage function. The hydro power plant capacity available for pumping, determined by generator unit outages, is binomially distributed.

The available pumping capacity has a discrete probability density function which by applying the Dirac function assumes the following shape:

$$f_p(P_{MP,i}) = P\ (P_{MP,i})\ \delta\ (P_{MP} - P_{MP,i}); \quad i = 0,\ 1,\ 2,\ ...,\ n\ , \qquad (38)$$

gdje je :

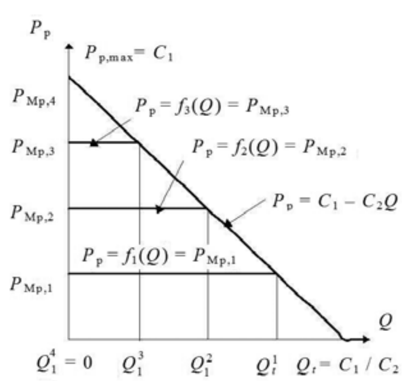
i – indeks stupnja snage crpljenja ili broj crpki spremnih za pogon,
$P(P_{MP,i})$ – vjerojatnost stupnja snage.

Svakom opsegu snage od ukupno n crpki hidroelektrane pridodaje se m stupnjeva snage. Uz pretpostavku konstantnosti bruto padova i stupnjeva korisnog djelovanja, moguća su dva slučaja. Prvi je da su broj crpki spremnih za pogon i njihova snaga dovoljni za crpljenje one količine vode u gornji akumulacijski bazen s kojim će se uz vodu iz prirodnog dotoka moći proizvesti potrebna energija iz crpno-akumulacijske hidroelektrane $W_{vt,max}$. Na krivulji $P_p = f(Q)$ (slika 5) za rastuće dotoke to znači nalaženje na njezinom padajućem dijelu.

where:

i – index of pumping capacity rate or the number of pumps ready for operation,
$P(P_{MP,i})$ – capacity rate probability.

To each capacity volume of n pumps of the hydro power plant m capacity rate is added. Assuming that gross falls and efficiency rates are constant, two scenarios are possible. The first is that the number of pumps ready for operation and their capacities are sufficient for pumping as much water as necessary together with the natural inflow water to generate required electricity $W_{vt,max}$ from the pumped-storage hydro power plant. On the curve $P_p = f(Q)$(Figure 5) for growing inflows it means the position in its falling section.



Slika 5 – Familija krivulja $P_p = f(Q)$
Figure 5 – Family of curves $P_p = f(Q)$

Treba, dakle, odrediti vjerojatnost da snaga crpljenja uvjetovana ispadima i dotokom leži unutar pojedinih opsega snage i, tj. u intervalu s graničnim vrijednostima $P_{\mathrm{p},i,j}$ i $P_{\mathrm{p},i,j+1}$. Ta vjerojatnost jednaka je vjerojatnosti da je ispadima uvjetovana snaga crpljenja P_{MP} najmanje tolika koliko je potrebno za crpljenje količine vode Q_{p}, ovisne o dotoku Q koji se nalazi u intervalu s granicama $Q_{i,j}$ i $Q_{i,j+1}$. Tim graničnim vrijednostima dotoka odgovaraju stupnjevi snage crpljenja $P_{\mathrm{p},i,j}$ i $P_{\mathrm{p},i,j+1}$, a ovisnost je zadana linearnim dijelom krivuljew $P_{\mathrm{p}} = f(Q)$. Budući da su događaji međusobno neovisni, vjerojatnost složenog događaja jest:

Therefore, what should be determined is the probability that the pump capacity determined by inflows and outages lies within certain capacity volumes and in the interval with the marginal values $P_{\mathrm{p},i,j}$ and $P_{\mathrm{p},i,j+1}$. Such a probability is equal to the probability that the outage-determined pump capacity P_{MP} is at least as high as required for pumping the amount of water Q_{p}, dependent on inflow Q placed in the interval within margins $Q_{i,j}$ and $Q_{i,j+1}$. These marginal inflow values are matched by pump capacity rates $P_{\mathrm{p},i,j}$ and $P_{\mathrm{p},i,j+1}$, whereas dependence is given by the linear section of the curve $P_{\mathrm{p}} = f(Q)$. As the events are interdependent, the probability of a complex event is:

$$P'(P_{\mathrm{p},i,j} < P_{\mathrm{p}} \le P_{\mathrm{p},i,j+1}) = P(P_{\mathrm{MP}} \ge P_{\mathrm{MP},i}) \cdot P(Q_{i,j} < Q \le Q_{i,j+1})$$
$$i = 0,\ 1,\ 2,\ ...,\ n$$
$$j = 1,\ 2,\ ...,\ m\ . \qquad (39)$$

Funkcija razdiobe snage crpljenja glasi:

The pump capacity distribution function reads:

$$F'(P_{\mathrm{p},i,j+1}) - F'(P_{\mathrm{p},i,j}) = F^*(P_{\mathrm{MP},i})\left[F^*(Q_{i,j}) - F^*(Q_{i,j+1})\right]$$
$$i = 0,\ 1,\ 2,\ ...,\ n \qquad (40)$$
$$j = 1,\ 2,\ ...,\ m\ .$$

Vrijednost funkcije razdiobe na mjestu $(i, j+1)$ iznosi:

The value of the distribution function at the position $(i, j+1)$ is:

$$F'(P_{\mathrm{p}}) = F'(P_{\mathrm{p},i,j+1}) = F^*(P_{\mathrm{MP},i})\left[F^*(Q_{i,j}) - F^*(Q_{i,j+1})\right] - F'(P_{\mathrm{p},i,j})$$
$$i = 0,\ 1,\ 2,\ ...,\ n \qquad (41)$$
$$j = 1,\ 2,\ ...,\ m\ .$$

U drugom slučaju, od ukupno n crpki za pogon je spremno i crpki, ali njihovi protoci nisu dovoljni da bi se uz prirodni dotok osigurala dovoljna količina vode potrebna da bi hidroelektrana proizvela količinu energije $W_{\mathrm{vt,max}}$. Količine vode koje dotječu prirodnim dotokom manje su ili jednake od količina koje odgovaraju snagama crpki u pogonu $P_{\mathrm{MP},i}$, što znači da vrijedi konstantni dio funkcije $P_{\mathrm{p}} = f(Q)$ na slici 5. Za svaki stupanj snage i vrijedi posebna karakteristika $P_{\mathrm{p}} = P_{\mathrm{MP},i} = \mathrm{konst}$. U tom slučaju raspoložive crpke rade punim opterećenjem $P_{\mathrm{MP},i}$. Stupnjevi snage crpljenja uvjetovani ispadima i dotokom su:

In the second scenario, out of n pumps i pumps are ready for operation, but their flows are not sufficient to provide enough water together with natural inflows required for the hydro power plant to generate electricity in the amount of $W_{\mathrm{vt,max}}$. The amounts of water from natural inflow are below or equal to the amounts corresponding to pump capacities in operation, $P_{\mathrm{MP},i}$, meaning that the constant section of function $P_{\mathrm{p}} = f(Q)$ (Figure 5) applies. To each capacity degree a specific characteristic $P_{\mathrm{p}} = P_{\mathrm{MP},i} = \mathrm{konst}$., applies. In that case the available pumps operate at full load $P_{\mathrm{MP},i}$. The outage-determined pump capacity rates and inflows are:

$$P_{p,i} = P_{MP,i} = i\ P_0, \quad i = 0,\ 1,\ 2,\ ...,\ n\ .$$

Zbog neovisnosti događaja, vjerojatnost nastupanja tih diskretnih stupnjeva snage jednaka je produktu vjerojatnosti pojedinačnih događaja, dakle:

Due to the independence of events, the probability of the occurrence of these discrete capacity rates equals the product of probability of single events, hence:

$$P''(P_{p,i}) = P(P_{MP} = P_{MP,i}) \cdot P\left\{Q \leq \left[Q_t^{(i)} = f^{-1}(P_{MP,i})\right]\right\}; \quad i = 0,1,2,\ldots,n\ . \qquad (42)$$

Funkcija gustoće i funkcija razdiobe vjerojatnosti za taj slučaj na mjestu i jest:

The density function and the probability distribution function for this case at position i is:

$$f''(P_{p,i}) = f(P_{MP,i}) \cdot F\left[Q_t^{(i)} = f^{-1}(P_{MP,i})\right], \quad i = 0,\ 1,\ 2,\ ...,\ n-1\ , \qquad (43)$$

$$F''(P_p) = \sum_{i=0}^{l} f''(P_{p,i})\ , \quad za \quad P_{p,i} \leq P_p < P_{p,i+1}; \quad l = 0,\ 1,\ 2,\ ...,\ n-1\ . \qquad (44)$$

$Q = f^{-1}(P_p)$ inverzna je funkcija funkcije prema izrazu (28).

Dva prethodno navedena slučaja pojave snage crpljenja crpno-akumulacijske hidroelektrane uvjetovane dotokom i ispadima međusobno su isključiva, tako da je vjerojatnost da se snaga crpljenja nalazi unutar intervala s graničnim vrijednostima $P_{p,i,j}$ i $P_{p,i,j+1}$ jednaka sumi vjerojatnosti prema izrazima (39) i (42). Funkcija razdiobe vjerojatnosti snage crpljenja jest:

$Q = f^{-1}(P_p)$ is an inverse function of the function according to expression (28).

The above two scenarios of the inflow- and outage-determined pumped-storage hydro plant's pumping power are mutually exclusive, so that the probability that the pump capacity is situated within the interval within marginal values $P_{p,i,j}$ and $P_{p,i,j+1}$ equals the sum of probabilities according to (39) and (42). The probability distribution function of pumping capacity is:

$$F(P_p) = F'(P_p) + F''(P_p)\ . \qquad (45)$$

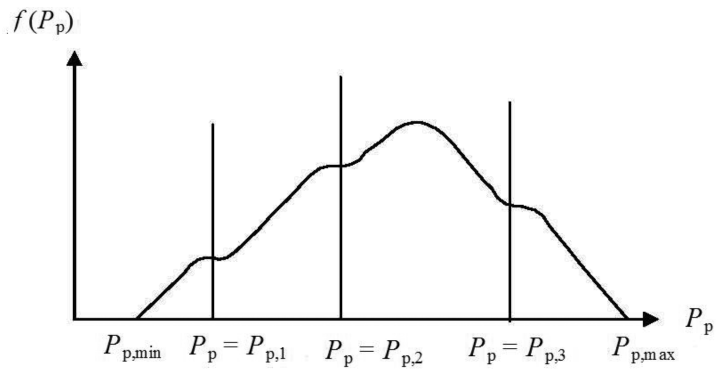
Iz funkcije razdiobe slijedi funkcija gustoće vjerojatnosti:

The probability density function follows from the distribution function:

$$f(P_p) = \frac{\mathrm{d}\,F(P_p)}{\mathrm{d}\,P_p}\ . \qquad (46)$$

Na mjestima $P_{p,i}$ pojavljuju se diskretni skokovi čija je visina određena izrazom (43) (slika 6).

On locations $P_{p,i}$ discrete leaps appear whose height is defined by expression (43) (Figure 6).



Slika 6 – Funkcija gustoće vjerojatnosti ispadima i dotokom uvjetovane snage crpljenja
Figure 6 – Probability density function of outage and inflow determined pumping capacity

Funkcija gustoće vjerojatnosti mora zadovoljavati uvjet:

The probability density function must meet the following requirement:

$$\int_{-\infty}^{\infty} f(P_p)\,\mathrm{d}P_p = \int_{0}^{P_{p,max}} f(P_p)\,\mathrm{d}P_p = 1\ . \quad (47)$$

Kod uključivanja crpno-akumulacijske hidroelektrane u model za proračun pouzdanosti potrebno je razmatrati i slučajeve koji mogu izazvati promjene u načinu rada tih postrojenja, a dolaze isključivo od strane sustava. Prvi je takav slučaj nemogućnost sustava da osigura dovoljno snage i energije za crpljenje vode u gornji akumulacijski bazen. Time se neposredno povećava rizik nedostatka vode. Drugi se pojavljuje kao posljedica iznenadne pojave manjka snage u sustavu koji izaziva potrebu da hidroelektrana kao jedinica s mogućnošću brzog starta kratkotrajno prekine crpljenje vode u gornji akumulacijski bazen i prijeđe u turbinski pogon, tj. preuzme dio ispalog opterećenja ostalih elektrana sustava. U tom drugom slučaju smatra se da hidroelektrana može vrlo brzo promijeniti način rada, te da će u turbinskom pogonu ostati sve dok se na drugi način ne pokrije ispalo opterećenje. Uz nedovoljno crpljenje javlja se i dodatni neplanirani potrošak vode iz gornjeg akumulacijskog bazena. U tom slučaju rizik nedostatka vode povećava se ako se ne može relativno brzo, tj. već tijekom istog ciklusa nadoknaditi taj dodatni neplanirani potrošak vode. Isti učinak ima i nemogućnost da se osigura snaga i energija za crpljenje zbog znatnog povećanja troškova. Rad u regulaciji normalno je pogonsko stanje koje znači i dugotrajniji potrošak vode.

When pumped-storage hydro power plants are included in the reliability calculation model it is also necessary to consider the cases which may bring about changes in the operation mode of such plants and which come exclusively from the system itself. The first such case is the system's inability to provide enough power for pumping water into the upper reservoir. This directly heightens the water deficiency risk. The second case occurs as a result of a sudden capacity shortage in the system creating a need that the hydro power plant as a unit with instantaneous start capacity discontinues water pumping into the upper reservoir for a short while and switches over to turbine drive, i.e., takes over a part of outage load of other plants in the system. In that second case the hydro power plant is deemed able to change the operation mode very quickly and stay in turbine drive as long as the load shortage is covered from other sources. In addition to insufficient pumping there is the additional unplanned water consumption from the upper reservoir. In that case the water deficiency risk increases if it is not possible to make up relatively quickly for such additional unplanned water consumption, i.e., already during the same cycle period. The same effect also comes from the inability to secure capacity and power for pumping due to significantly increased costs. The regulation operation is a normal condition, and that means prolonged water consumption.

5 ZAKLJUČAK

Razvijen je model za proračun pouzdanosti i raspoloživosti crpno-akumulacijske hidroelektrane. Razvijeni su kriteriji, mjerila i pokazatelji vrednovanja i iskazivanja razine pouzdanosti i raspoloživosti crpno-akumulacijske hidroelektrane uključujući i odgovarajuće rizike nedostatka dotoka i stanja zaliha vode u gornjem i donjem akumulacijskom bazenu, te njihova uključivanja u programske sustave za operativna planiranja rada elektroenergetskog sustava. Razvijeni modeli uzimaju u obzir složenost radnog ciklusa i jaku uvjetovanost ulaska u pogon i načina rada crpno-akumulacijske hidroelektrane o prilikama u elektroenergetskom sustavu, te načinu rada i specifičnim troškovima proizvodnje ostalih proizvodnih postrojenja, prvenstveno termoelektrana. Time je uspostavljen sustav za cjeloviti obuhvat i vrednovanje crpno-akumulacijske hidroelektrane pri operativnom planiranju rada elektroenergetskog sustava.

5 CONCLUSION

A model has been developed for calculating the reliability and availability of pumped-storage hydro power plants. The criteria and indicators have also been developed for the evaluation and determination of the reliability and availability levels of pumped-storage hydro power plants, including the risks of inflow deficiency and water storage in the upper and lower reservoirs and their inclusion in the programme systems of planning the power system operation. The developed models take into account the complexity of the operation cycle and strong dependence of the operation mode of the pumped-storage hydro power plants on the conditions prevailing in the power system and on the operation mode and specific generation costs of other power plants, primarily thermoelectric power plants. A system has thus been put in place for integrated coverage and evaluation of pumped-storage hydro power plants in planning the power system operation.

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