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MARKOV CHAIN MODEL FOR SMALL HYDRO POWER PLANT RELIABILITY AND OPERATION EVALUATION

Full paper

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Abstract: High penetration of renewables into the electrical power system decreases the reliability of energy supply. Due to their simplicity and easy demand satisfaction, small hydro power plants (SHPP) are the most exploited. Therefore, reliability estimation and performance evaluation of SHPP are of great importance for proper maintenance. In this paper reliability of network connected run-of-river SHPP will be reviewed, considering different operational and technical conditions that cause unavailability, using Markov chain. The unavailability situations scenario inspects the behaviour of the hydro units in a certain period of time and the inflow rates. The model is used for performance evaluation and analysis of the worst case scenario.
Key words: Small hydro power plants, Markov chain, reliability, performance evaluation

1. INTRODUCTION

The idea of creating a “perfect” power network, which is self-healing, has a high availability and can remove the causes of failure fast, has been challenging the researchers and the engineers ever since the smart grids were developed. The increased penetration of Renewable Energy Sources (RES) into the classical power network has a high impact on the power network reliability. It is highly affected by their dependence on the weather conditions. In order to maintain the quality of power production and security of supply, the number of failures of the components in the power plants, substations and power lines should be reduced. Since there is no failure free network, the accent should be put on fast indication and restoration of the failed equipment. In that regard, methods for evaluation of operation performance and estimation of reliability are being developed.

Hydropower, as a RES, has been certified as a clean and efficient source of power for centuries. Most hydropower plants can easily adjust the water flow through the turbine, but in case of run-of-river (ROR) power plants, which are the aim of this paper, the water flow depends on river inflow, i.e. on the hydrological conditions. ROR power plants do not have water storage at all or a limited amount of storage, which makes them less reliable than the other types of hydropower plants. But on the other hand, their simplicity and capability of adjustment into the environment characteristics, not threatening the eco-system, has made them more favourable and lured the engineers.

Increased interest in SHPP concession in Republic of North Macedonia requires a proper reliability estimation model to calculate the risk, reliability and economically justify the SHPP projects. In the last decade, many models for reliability estimation based on different mathematical methods were presented. But, as far as known, the mutual impact of the river inflow and generation availability, taking into account the probability state transitions, using Markov chain, has not been analysed. In this paper, a model for reliability estimation of power generation and operation performance evaluation of network connected SHPP, which takes into account technical conditions of uncertainty, and the production probability of the SHPP units depending on the inflow, based on Markov chain, is presented. The model analyses the probability of worst-case scenarios, combining the probability of inflow occurrence and units' failure probability.

The interest in Markov chain model and its application is that it provides easy and simple analysis of hydro power systems considering only the previous state. The performance of SHPP depends on the current inflow rate and service life of installed technical equipment, which can easily be modelled by Markov chain model.

2. RELATED WORK

The interest in Markov chain model applicability for reliability estimation of power plants has increased in the last few years. There are many publications that analyse the power systems using Markov models, proving that Markov chain model can be applied for majority of real life systems. In the following three scientific papers that examine the application of Markov chain model for SHPP reliability estimation and are considered to be similar to the topic of this paper are reviewed.

In [1] a model for scheduling and optimisation of maintenance and renewal of hydro power plants is presented. The proposed method estimates the parameters of hydro systems describing the technical condition of components and systems according to the Norwegian Electricity Industry Association. The model is time dependent, i.e. the probability that the system is in a certain state is given as a function of the time. That means that the duration of inspection interval is not constant but the time of the next inspection depends on the inspection result. The method has a certain limitations, but sets the ground for further scientific work.

In [2] a model for generation availability of SHPP evaluation is presented. The model consists of the river inflow model and generation unit model. The river inflow model considers the inflow uncertainties represented with clustering techniques k-means in two different approaches: inflow clustering and power clustering. The generation unit model is a two state model, considering the two operational conditions of the units: operating or failed. The model is used for computation of the expected value of the annual power generation of the SHPP, the duration curve, and reliability.

In [3] the same model, as in [2], is applied on a real case of Norwegian river to demonstrate the applicability of the model, and also the reliability of energy-limited ROR hydro-electric generation systems is examined. The model consists of two state generation and multistate inflow model and it considers the uncertainties of river inflows and generation units' operation. In that model, the substation equipment, including the generator reliability is not impacted by the inflow rates, and the generator model consists of two states: failed and operating. In this paper, the state transition rates of installed generators and the inflow state transition rate are analysed, computing the mutual impact. The inflow model is based on the one presented in [3], but it analyses only the most important values of the inflow, the ones most influential for power generation.

The main uncertainty regarding the output power of a ROR power plant is due to the inflow of water. The reason for this is that a ROR cannot fully regularize its water usage, as the power plant only has a small or no reservoir at all. Since the water inflows can have a big variation throughout a year and can shift seasonally and regionally, it is important to incorporate this uncertainty in reliability studies [3].

3. MARKOV CHAIN MODEL

Markov chain, named after the Russian mathematician Andrey Markov, is a stochastic model, also known as memoryless model, because its probability depends only on previous event. It finds its application in many different fields, mostly for weather forecasting, genetic networks, DNA sequences, typing word prediction, credit risk management etc. Its best known application is in Google Page Rank.

Markov models are used for availability analysis of series or parallel system, in which one element is in outage (has failed or is being repaired). The Markov model evaluates the probability of moving from one state to another until the system has reached the final failed state [4]. State transition diagrams are used to define the probability transitions from the initial to the final state. The complexity of the diagrams depends on the number of states, which is calculated as a power of two (2^{n}). For example, if there are 10 elements and each of the elements has two states (normal operating and failed), total number of states is: $2^{10} = 1024$. If the number of elements increases for 1 element, the total number of states enlarges twice. The advantage of

Markov chain is the capability of its application even when the system is divided in two subsystems. For example, if the system of 10 elements is divided into two subsystems consisting of 5 elements, also with two states, the total number of states is $2 \cdot 2^5 = 2 \cdot 32 = 64$, resulting with a way smaller system, which can easily be solved [3].

One of the advantages of using Markov chain model is that it allows computing steady state probabilities of all system states, which helps in probabilities estimation of rare events and failure scenarios [5]. The Markov chain describes a system as a discrete set of states with possible transitions among them. In life, many natural processes can be explained with Markov chain, containing all the information that is part of the processes. Therefore the size of state space can be large (thousands or millions of states), thus numerical modelling techniques must be applied [5]. The Markov method is a very simple method, which considers failure rates of the system providing complex system to be modelled in simple manner by applying semi-Markov method. The Markov method improvement and application to all or any engineering application are justified and supported by two international standards: IEC61165 and IEC 61508 [4][6]. IEC 61165 provides guidance on the application of Markov techniques to system reliability and availability estimation modelling [7]. IEC 61508 defines the functional safety and electrical or electronic safety-related systems [8].

In this paper, the usage of Markov chain model for reliability estimation is justified by its capability for simplifying complex systems and providing simpler analysis. Since the SHPPs' proper work depends on the current state of the inflow, and modelling the inflow is a complex work, its probability is best to estimate using Markov mathematical model.

4. MODEL FOR SHPP RELIABILITY ESTIMATION

Despite the high level of automation and technology applied for maintenance and monitoring, in today's electric power production process using water is still fighting the way with the technical failures to reliable generation. Also, in electrical transmission and distribution network, the biggest concern is in dealing with outages, thus maximizing the capability to transmit power to end-customers. Outages are normally due to maintenance but could also be caused by repair work after failures [9]. To prevent such uncertainty a detailed system behavioural analysis along with maintenance planning is very important. Another major obstacle is avoiding any blackouts for power consumers, substation failures, or loss of connection to generating power stations. Such events are entirely related to unplanned activities due to a failure of some kind (short circuit, lightning strike, equipment failure etc.). The "quality" of a certain substation in this respect is often expressed as reliability or how failure tolerant it may be [9].

Reliability is a probability certain device or system performing adequately according to previously established conditions. In this case, it is proper and safe working of the equipment, serving and providing the required data from the measurement units. The failures of the equipment are mostly caused by mechanical or electrical nature, and also, not so often, caused by human errors. Each of the components in the power network has a certain reliability index. It demonstrates the number of failures occurred in a certain period of time. And since the components connected form a system, the reliability of the system is computed using the proposed method.

SHPP substation elements reliability is calculated by the number of failures, the duration of the failures, the number of elements examined and the mean time to repair. The SHPP substation elements include: generator, transformer, disconnector and circuit breaker, as shown on Figure 1. The measurement and protection elements are not taken into consideration, since their work does not affect the power generation and supply. In this paper, turbine reliability is not calculated as a distinctive part of the SHPP substation, but its reliability depends on the inflow rate and it is calculated along with the generator reliability, denoted as hydro unit reliability.

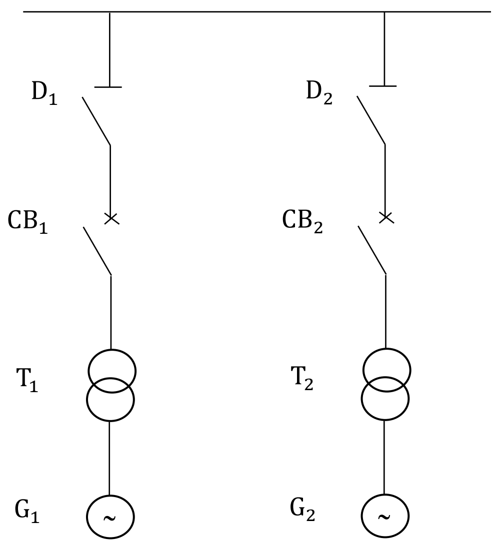

Figure 1 Single-line diagram of a typical SHPP with two units

Generator failure rate differs from one hydro generator to another, and therefore its failure rate is taken from statistical reviews. The elements in the substation can be connected in series or parallel. Equivalent reliability computation of series system is shown with eq. (1), and equivalent reliability of parallel system is shown with eq. (2).

$$\lambda_{series,eq} = \sum_{i=1}^{m} \lambda_i \tag{1}$$

$$\lambda_{parallel,eq} = \prod_{i=1}^{n} \lambda_i \tag{2}$$

The SHPP reliability model combines the river inflow model and the generator model. The two models are interfered, meaning that the generators working conditions are influenced by the variations of the river inflow and inversely. An inflow time series usually contains many different inflow values, whose manipulation may be time consuming, and therefore a mean monthly inflow rates are analysed.

SHPP working condition strongly depends on equipment safe and normal operation. The state matrix takes into account the states most probable to happen, assuming that the probability of the state depends only on the previous state and that the process is stationary, i.e. the transitions rates between the states need to be constant throughout the process. The proposed approach in this paper analyses the transition of states of the hydro units (turbine and generator connection) of SHPP. That means that the reliability of the units is given as a matrix consisting of the probabilities of moving from one state to another. The units' state matrix takes into account all kinds of outages, whether caused by failure or due to maintenance.

For example, in the state of two failed units, the probability of transferring to the state of normal operation, when two of the units are operating is low compared to the probability of transferring to the state when one unit in operating (the failure is temporary or it is removed) or continuing the present state of two units failed. The substation elements, including units' failure probabilities are given as a matrix A:

$$\mathrm{A}_{(n+1)\times(n+1)} = \begin{vmatrix} a_{0\to 0} & a_{0\to 1} & a_{0\to 2} & \cdots & a_{0\to n} \\ a_{1\to 0} & a_{1\to 1} & a_{1\to 2} & \cdots & a_{1\to n} \\ & & \vdots & \ddots & \vdots \\ a_{n\to 0} & a_{n\to 1} & a_{n\to 2} & \cdots & a_{n\to n} \end{vmatrix} \tag{3}$$

Where, n is the number of units, and the units' state transition probabilities are denoted as $a_{i\to n}$, where $\forall i \in \mathbb{Z}^{\geq 0}$.

The zero (0) state represents the most positive state, meaning that all units are in working condition. Any other state $(1, 2, \dots, n)$ represents the number of failed units. The units are connected to the other elements in the branch in series, and the branches are connected in parallel. The equivalent reliability vector of the components in the examined system is computed as:

$$\lambda_{1\times(n+1)} = \begin{vmatrix} 1 - \prod_{j=1}^{n} \sum_{i=1}^{m} \lambda_{i,j} & \sum_{\substack{i=1 \\ j=k}}^{m} \lambda_{i,j} & \prod_{j=1}^{2} \sum_{i=1}^{m} \lambda_{i,j} & \cdots & \prod_{j=1}^{n} \sum_{i=1}^{m} \lambda_{i,j} \end{vmatrix} \tag{4}$$

Where,

$n -$ number of units is equal to the number of branches;

$m -$ number of elements;

$k -$ the number of the unit in outage;

$\lambda -$ component unavailability ;

The generation of electricity in SHPP also depends on inflow rates. The matrix of states' transitions, regarding the water inflow, is a square matrix and it has the same number of states as the units' state matrix. The states boundaries are previously defined and they defer from case to case. In this matrix, the initiate state is denoted as L, and it indicates a very low inflow, incapable to run any of the units.

$$\mathrm{I}_{\mathrm{fl},(\mathrm{n}+1)\times(\mathrm{n}+1)} = \begin{vmatrix} q_{L\to L} & q_{L\to 1} & q_{L\to 2} & \cdots & q_{L\to n} \\ q_{1\to L} & q_{1\to 1} & q_{1\to 2} & \cdots & q_{1\to n} \\ & \vdots & & \ddots & \\ q_{n\to L} & q_{n\to 1} & q_{n\to 2} & \vdots & q_{n\to n} \end{vmatrix} \tag{5}$$

In Figure 2 the state transitions of n-state systems is shown.

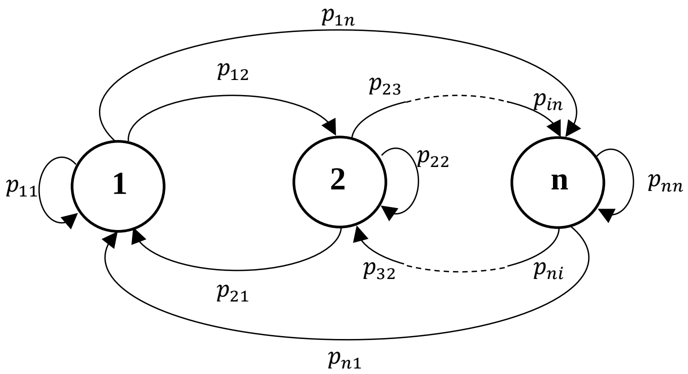

Figure 2 State transitions of n-state system

The probability of the inflow occurrence depends on the previous inflow. In other words, if the inflow in a specific moment is very low to run any of the hydro units, the possibility that the inflow in the next moment is high enough to run two hydro units is really low. Logically, the inflow rate has to be high enough to run one hydro unit first, and then two units. For simpler analysis, in this paper, a monthly inflow for a 10 year time period is analysed.

Probability of an event occurrence is calculated as a ratio of the number of events whose probability is being computed, and the total number of events.

$$p_{i,j} = \frac{\sum_{i=0}^{T} \sum_{j=1}^{N} E_{i,j}}{\sum_{i=0}^{T} TE_i} \tag{6}$$

Where,

$p_{i,j}$ – the probability of event occurrence;

N – number of states;

T – time duration of examination;

TE – total number of events;

E – number of events examined.

The total SHPP reliability is a product of the components reliability and the states' transitions matrices of the inflow and the units installed is shown with eq. (7).

$$\mathrm{R_{SHPP}} = \lambda_{1\times(n+1)} \cdot \mathrm{A}_{(n+1)\times(n+1)} \cdot \mathrm{I}_{fl,(n+1)\times(n+1)} =$$

$$\left|1-\sum_{i=1}^{n}\lambda_i \quad \sum_{i=1}^{n}\lambda_i \quad \sum_{i=1}^{n}{\lambda_i}^2 \quad \ldots \quad \sum_{i=1}^{n}{\lambda_i}^{n-1}\right| \cdot$$

$$\begin{vmatrix} a_{0\to 0} & a_{0\to 1} & a_{0\to 2} & \cdots & a_{0\to n} \\ a_{1\to 0} & a_{1\to 1} & a_{1\to 2} & \cdots & a_{1\to n} \\ & & \vdots & \ddots & \vdots \\ a_{n\to 0} & a_{n\to 1} & a_{n\to 2} & \cdots & a_{n\to n} \end{vmatrix} \cdot \begin{vmatrix} q_{L\to L} & q_{L\to 1} & q_{L\to 2} & \cdots & q_{L\to n} \\ q_{1\to L} & q_{1\to 1} & q_{1\to 2} & \cdots & q_{1\to n} \\ & & \vdots & \ddots & \\ q_{n\to L} & q_{n\to 1} & q_{n\to 2} & \vdots & q_{n\to n} \end{vmatrix} =$$

$$\left|\mathrm{r}_1 \quad \mathrm{r}_2 \quad \mathrm{r}_3\right| \tag{7}$$

The result is a row-vector which contains the probability rates of the worst-case scenario, for instance the probability of low river inflow when all of the units are in working condition or the probability of high river inflow when all of the units are failed.

5. TEST EXAMPLE

In this section, the previously presented approach will be demonstrated on a case scenario of a small run-of-river hydro power plant. The single line diagram of the SHPP is shown on Figure 1.

As previously shown, the technical data of the equipment is not relevant in the presented approach. But the inflow rate of the turbine is important for determination of the inflow rates' limits and building the river inflow rates transition matrix. The system consists of two identical Pelton wheel turbines each with technical parameters given in Table 1.

Table 1. SHPP turbine data

Number of units	2
Turbine type	Pelton
Inflow rate	0,3 m^3/s
Power rate (per unit)	146 kW

It is assumed that the inflow rates for several years and the unavailability rates of the equipment installed in the SHPP substation are known from statistical analyses. The river's average monthly inflow by year is given in Table 2, and the equipment's unavailability rates are given in Table 3.

Table 2. Average monthly inflow data

Year	$Q[\mathrm{m}^3/\mathrm{s}]$											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Noe	Dec
2001	0,196	0,286	0,645	1,194	0,623	0,32	0,196	0,127	0,127	0,374	0,237	0,878
2002	0,28	0,205	0,198	0,658	0,482	0,225	0,07	0,10	0,044	0,07	0,07	0,394
2003	0,221	0,171	0,437	0,10	0,365	0,221	0,148	0,07	0,148	0,10	0,221	0,274
2004	0,21	0,137	0,10	0,10	0,10	0,175	0,104	0,087	0,054	0,10	0,10	0,10
2005	0,196	0,171	0,221	1,157	0,10	0,158	0,054	0,10	0,10	0,10	0,239	0,10
2006	0,10	0,10	0,478	0,10	0,10	0,32	0,168	0,10	0,10	0,10	0,10	0,10
2007	0,469	0,589	0,103	1,074	0,852	0,255	0,204	0,148	0,12	0,105	0,147	0,352
2008	0,216	0,261	0,10	0,729	0,365	0,248	0,02	0,10	0,10	0,10	0,269	0,308
2009	0,123	0,161	0,506	0,854	0,642	0,315	0,10	0,10	0,10	0,10	0,10	0,356
2010	0,266	0,25	0,318	0,356	0,264	0,195	0,14	0,111	0,132	0,118	0,236	0,279
2011	0,23	0,22	0,65	0,925	1,288	0,457	0,21	0,168	0,14	0,129	0,46	0,278
2012	0,157	0,158	0,2	0,58	0,353	0,228	0,171	0,116	0,107	0,285	0,506	0,269
2013	0,161	0,152	0,296	1,269	0,388	0,203	0,136	0,116	0,139	0,132	0,192	0,612
2014	0,44	0,263	0,608	0,919	0,353	0,192	0,179	0,154	0,158	0,129	0,167	0,141
2015	0,905	0,275	0,464	1,099	1,586	0,266	0,182	0,168	0,211	0,163	0,349	1,468
2016	0,613	0,167	0,183	1,38	2,008	0,288	0,135	0,183	0,318	0,3	0,672	2,481

Table 3. Equipment reliability

Component	*Symbol*	*Voltage [kV]*	*Unavailability rate*
Transformer	λ_{TR}	0,4/10	$1{,}138 \cdot 10^{-4}$
Circuit breaker	λ_{CB}	10	$1{,}953 \cdot 10^{-5}$
Disconnector	λ_D	10	$3{,}465 \cdot 10^{-5}$

On Figure 3 the state transition of inflow rates and technical conditions of three state systems is shown.

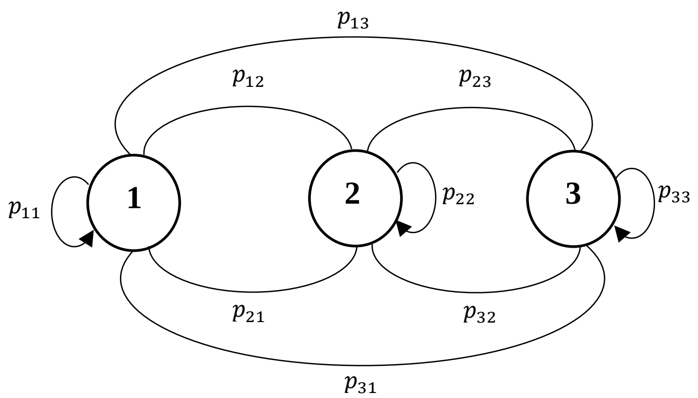

Figure 3 State transition of three state system

Using eq. (1), (2), the equivalent reliability of one branch is calculated and is represented as in eq. (4).

$$\sum_{I=1}^{3}\lambda_i = \lambda_{TR} + \lambda_{CB} + \lambda_D = 1{,}138 \cdot 10^{-4} + 1{,}953 \cdot 10^{-5} + 3{,}465 \cdot 10^{-5} = =1{,}680 \cdot 10^{-4} \tag{8}$$

$$\lambda_{1\times 3} = |0{,}999 \quad 1{,}643 \cdot 10^{-4} \quad 2{,}822 \cdot 10^{-8}| \tag{9}$$

The equipment technical conditions are:

$$\begin{cases} 0, & normal\ run \\ 1, & one\ unit\ out \\ 2, & two\ units\ out \end{cases}$$

$$A_{3\times 3} = \begin{vmatrix} a_{0\to 0} & a_{0\to 1} & a_{0\to 2} \\ a_{1\to 0} & a_{1\to 1} & a_{1\to 2} \\ a_{2\to 0} & a_{2\to 1} & a_{2\to 2} \end{vmatrix} = \begin{vmatrix} 0{,}60 & 0{,}03 & 0{,}04 \\ 0{,}03 & 0{,}23 & 0{,}01 \\ 0{,}001 & 0{,}03 & 0{,}03 \end{vmatrix} \tag{10}$$

In this paper the following order of inflow states is determined:

$$\text{If} \begin{cases} q_i \le 0{,}3\ [\mathrm{m}^3/\mathrm{s}] & then, the\ inflow\ is\ too\ low\ to\ run\ any\ of\ the\ units \\ 0{,}3 < q_i \le 0{,}6\ [\mathrm{m}^3/\mathrm{s}] & then, the\ inflow\ is\ high\ enough\ to\ run\ one\ unit \\ 0{,}6 < q_i \le 1{,}2\ [\mathrm{m}^3/\mathrm{s}] & then, the\ inflow\ is\ high\ enough\ to\ run\ two\ units \end{cases}$$

If the inflow rate is higher than 1, 2 [m^3/s], then the excess water is diverted around the hydro power plant.

Using the eq. (6), determined conditions and data from Table 2 the transition rates are calculated and given in eq. (8).

$$I_{fl,3\times 3} = \begin{vmatrix} q_{L\to L} & q_{L\to 1} & q_{L\to 2} \\ q_{1\to L} & q_{1\to 1} & q_{1\to 2} \\ q_{2\to L} & q_{2\to 1} & q_{2\to 2} \end{vmatrix} = \begin{vmatrix} 0{,}56 & 0{,}09 & 0{,}05 \\ 0{,}12 & 0{,}02 & 0{,}01 \\ 0{,}04 & 0{,}04 & 0{,}04 \end{vmatrix} \tag{11}$$

Finally, the SHPP reliability and performance evaluation are calculated using eq. (7).

$$R_{SHPP} = \lambda_{1\times 3} \cdot A_{3\times 3} \cdot I_{fl,3\times 3} = |0{,}999 \quad 1{,}643 \cdot 10^{-4} \quad 2{,}822 \cdot 10^{-8}| \cdot \begin{vmatrix} 0{,}60 & 0{,}03 & 0{,}04 \\ 0{,}03 & 0{,}23 & 0{,}01 \\ 0{,}001 & 0{,}03 & 0{,}03 \end{vmatrix} \cdot \begin{vmatrix} 0{,}56 & 0{,}09 & 0{,}05 \\ 0{,}12 & 0{,}02 & 0{,}01 \\ 0{,}04 & 0{,}04 & 0{,}04 \end{vmatrix} = |0{,}341 \quad 0{,}058 \quad 0{,}033| \tag{12}$$

The result gives information of the possibility of three worst scenarios most likely to happen. As from the result, it can be concluded that the probability of high river inflow occurrence, while all of the hydro units are in outage is very low. That shows the high dependability of power generation on the river inflow.

The proposed model can be applied for economical evaluation of ROR projects and risk analysis in the process of SHPP design. Another application of the reliability vector of SHPP is to calculate the energy not supplied (ENS), by multiplying it with the installed power capacity of the SHPP and the number of hours per year. The result is also a vector, containing the energy not supplied in the three most likely to happen, worst-case scenarios.

$$ENS_{SHPP} = R_{SHPP} \cdot P_{installed} \cdot T_{year} = |0{,}341 \quad 0{,}058 \quad 0{,}033| \cdot 146 \cdot 2 \cdot 8760 =$$

$$|872{,}245 \quad 149{,}569 \quad 85{,}430| \; [MWh/year] \tag{13}$$

The first element in the vector indicates the ENS when the river inflow is too low to run any of the units, while all of the hydro units are in operating mode. The second element gives the information about ENS when the river inflow is high enough to run one unit, while one hydro unit is in outage. The last element responds to situation of high inflow, while all of the hydro units are in outage.

6. CONCLUSION

In this paper the application of Markov chain for SHPP operation evaluation was presented and the factor of mutual dependency of water inflow and generation equipment was calculated. It was shown that using the Markov chain for operation analyses and reliability estimation of SHPP provides simple and accurate calculation. The presented model can serve as a base for further development in economic cost-efficiency of SHPP project, considering the hydrological conditions and operating service of the installed equipment. Also, it can be applied on any power system operation evaluation. The future scope of research is to extend the developed model further and make it more effective.

The first advantage of the proposed approach is that it is based on an already existing state definition. Instead of introducing a new concept for the technical conditions of hydro power systems an advantage was taken of the existing two state models and the transition matrix was formed. Another advantage is that it does not take into account the technical characteristics of the equipment (type of generator or turbine, number of rotations, power factor etc.); instead it just uses the unavailability rates. This allows further analysis of the environmental conditions on system performance. Also, the approach can be easily programmed into the power engineering projects to reduce the time for risk calculations.

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