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RELIABILITY EVALUATION OF POWER SUPPLY OF DISTRIBUTION GENERATION USING MARKOV CHAIN MODEL

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A b s t r a c t: The implementation of Renewable Energy Sources has been proven to be beneficial for local consumers. However, their dependency on weather conditions has a major impact on the reliability of the power supply. This paper presents a method for reliability evaluation of distributed generation, considering the probability of certain weather conditions occur. The method is based on the Markov chain model and considers the probabilities of operational and outage state occurrence. The case study analyzes a radial distribution network consisting of three Distribution Energy Resources (DERs) and a cluster of industrial consumers during distribution substation outage. The results describe three scenarios considering the availability of power generation of DERs and the occurrence of favourable weather conditions.

Key words: distributed energy resources; reliability; Markov chain model

ПРОЦЕНА НА ДОВЕРЛИВОСТА НА ИСПОРАКА НА ЕЛЕКТРИЧНА ЕНЕРГИЈА ОД ДИСПЕРЗИРАНО ПРОИЗВОДСТВО СО ПРИМЕНА НА МАРКОВИОТ МОДЕЛ НА ВЕРИГИ

А п с т р а к т: Имплементацијата на обновливите извори на енергија (ОИЕ) се покажа како корисна за локалните потрошувачи. Меѓутоа, нивната зависност од временските услови има големо влијание врз доверливоста на испораката на електрична енергија. Во овој труд е предложен метод за процена на доверливоста, кој ја вклучува веројатноста за појава на одредени временски услови. Методот базира на Марковиот модел на вериги и ги зема предвид веројатностите за нормален погон и испад. Методот е анализиран на случај на испад на дистрибутивна трафостаница во радијална дистрибутивна мрежа, која се состои од три дисперзирани генератори (ДГ) и индустриски потрошувачи. Резултатите ја прикажуваат веројатноста од појава на три сценарија кои ги земаат предвид способноста на генераторите за нормална оперативна работа и појавата на поволни временски услови.

Клучни зборови: дисперзирани генератори; доверливост; модел на вериги на Марков

1. INTRODUCTION

Due to the increase in environmental pollution and decrease of the global reserves of coal and oil, the researchers are looking for proper alternatives regarding the Renewable Energy Sources (RES). Distributed Energy Resources (DERs) are low scale power generation facilities, incorporated into the distribution network, which produce power from RES. DERs main function is to produce clean energy for local consumption. However, they make quite a contribution to the main power system.

DERs come with many benefits for the consumers as well as for the utility grid. They require lower operation and maintenance costs, come useful for load peak satisfaction, no need for long transition power lines investment and they are environmental-friendly. Therefore, considering that the prices for their installation are decreasing, the number of DERs installed in the distribution networks is rapidly growing.

The high penetration of RES into the distribution network increases the reliability of power supply to the local consumers.The distribution generation units cannot be analyzed as standard power generation units, due to their inconsistency of power generation. That affects the power system, causing disturbances and power supply interruptions and outages. Therefore, they are often supported by storage systems or back-up generators which capture the excess power generated from the power plants and enable its further usage.

Evaluation of reliability is an important part of the distribution network design process when DERs are incorporated. The reliability of supply in distribution network with implemented DERs is of great importance regarding the power supply of the consumers, especially for the clusters of consumers which are designed for islanded operation.

The researchers have been analyzing this issue, proposing different methods for reliability estimation ever since the DERs are actively being implemented into the standard power systems. However, the weather conditions have crucial importance and they have to be considered along with the availability rate of the installed equipment.

The interest in the Markov chain model and its application regarding this issue is that it provides an easy and simple analysis of weather conditions considering only the previous state. Weather is changeable, but the probability of occurrence depends mainly on the previous state, and that can be modelled with the Markov chain model. The inconsistency is the main characteristic of the majority of power engineering systems. Therefore, the Markov chain model applicability for reliability estimation of power plants has increased in the last few years.

In this paper, the reliability of the distribution network with connected different types of DERs is evaluated. The proposed method is based on the Markov chain model and considers the uncertainty of weather conditions, creating a vector of probabilities of different case scenarios occurrence, which may lead to power supply interruption.

The presented method is applied to a distribution network with three different DERs connected. The results are presented in table enabling easy calculation of the reliability indexes, such as Energy Not Supplied (ENS)

2. RELATED WORK

In [1] the Markov chain model is used for reliability estimation of cogeneration power plant substation. For that purpose, stochastic automata networks are formed. The substation is divided into smaller parts so that the state space of the Markov chain model is reduced. The results show that failure and repair rates of the transformers have a major effect on system availability.

In [2] a model for evaluation of generation availability of small hydropower plants (SHPP) is presented. The model considers the uncertainties regarding SHPP power production. The presented model consists of two parts: the river inflow model and the unit operation model. The river inflow is modelled as a stochastic process so that the random variables represent the inflow. The uncertainties regarding the inflow are represented with clustering techniques *k*-means in two different approaches: inflow clustering and power clustering. The unit generation model is a two-state model, considering two states: operating and failed. The model is used for calculation of the probability of power generation, the duration curve, and the reliability of the SHPP.

In [3] multiple methods for reliability estimation of hydro units are examined. The model presented in [2] is applied to a real case of Norwegian river. This paper demonstrates the applicability of the model and examines the reliability of energy-limited run-of-river (ROR) hydro-electric generation systems. The model consists of two state generation and multistate inflow model. However, it considers the uncertainties of multiple components regarding the generation units' operation. In the paper, the inflow rates of the model do not impact the units' reliability, and the unit model consists of two states: failed and normal operating.

In [4] a method for reliability evaluation of SHPP, regarding the inflow rate is proposed. The method is based on the Markov chain model. The state transition rates of installed generators and the inflow state transition rates are analyzed, computing the mutual impact. The inflow model is based on the one presented in [3], but the paper analyzes only the most important values of the inflow, the ones most influential for power generation, creating a multi-state Markov chain model.

In this paper, the method presented in [4] is upgraded for reliability estimation of a cluster of DERs, regarding different weather conditions.

3. MARKOV CHAIN MODEL

Markov chain model is a mathematical tool used for probability calculation of system transition from one state to another. The Markov chain model 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.

It is a stochastic memoryless model. The probability of one event occurrence depends only on the previous state, and it does not analyze the history of events. The probability of moving from one state to another is evaluated until the system reaches the final failed state, a point from where the system has to start from the beginning [5]. State transition diagram is shown in Figure 1..

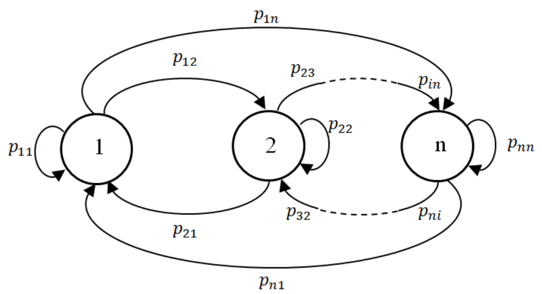

Fig. 1. State transitions of the *n*-state system

The complexity of the diagrams depends on the number of states. The advantage of the Markov chain model is the capability of its application even when the system is divided into two subsystems [3]. The Markov chain model is presented with a transition matrix, where p_{ij} denotes the probability of transferring from one state to another, and p_{ii} denotes the probability of continuing the work in the same state.

$$P_{n\times n} = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \vdots & & \ddots & \vdots \\ p_{n1} & p_{n2} & \cdots & p_{nn} \end{bmatrix} \qquad (1)$$

There are generally two types of Markov chain model. The first type is not time-dependent and the probabilities are calculated from statistical data for weeks, months or years and they are constant, unchangeable. The second type of Markov chain model considers the probabilities of state transferring which change over time [6].

Markov chain model has multiple advantages, among which is its capability of computing steady-state probabilities of all system states which helps in probabilities estimation of rare events and failure scenarios [5]. The model describes a system as a discrete set of states with possible transitions among them.

Many natural processes which contain large information can be described with the Markov chain model. That leads to large state spaces with thousands or millions of states. Thus numerical modelling techniques must be applied [5]. The application of Markov chain model provides a complex system to be modelled simply.

In this paper, the usage of the Markov chain model for reliability estimation is justified by its capability for simplifying a large amount of information regarding the complex systems and providing simpler analysis. Since the DERs, proper work depends on the current state of the weather conditions, and their modelling is a complex work, its probability is estimated using the Markov chain model. The probabilities for each state occurrence are considered to be time constant.

4. RELIABILITY EVALUATION OF DERs

Reliability is a probability indicator that a certain device or system is performing according to previously established conditions and constraints. In this paper it defines as a proper and safe working of the equipment, serving and providing the required data from the measurement units under defined conditions. The equipment failures are mostly caused by mechanical, electrical nature or by human errors. Each of the components in the power network has a certain unavailability index, which denotes the number of failures occurred in a certain period.

The reliability of the system depends on the state transition matrix of the weather conditions, the state transition matrix of the substation equipment and the reliability vector of the DERs.

In this paper, the equipment reliability matrix considers the transition of multiple states: operational state, state of an outage and partial operational state. The weather conditions matrix considers the weather conditions that refer to the DERs.

Regarding the equipment transition matrix, the probability of transferring from the state of normal operation to the state of an outage is higher, then vice versa. The substation elements, including units' failure probabilities, are given as a matrix A:

$$\mathrm{A}_{n\times n} = \begin{vmatrix} a_{0\to0} & a_{0\to1} & \cdots & a_{0\to n} \\ a_{1\to0} & a_{1\to1} & \cdots & a_{1\to n} \\ \vdots & & \ddots & \vdots \\ a_{n\to0} & a_{n\to1} & \cdots & a_{n\to n} \end{vmatrix} \qquad (2)$$

where n denotes the number of DERs and the equipment's state transition probabilities are denoted as $a_{i\to j}$, where $\forall i \in \mathbb{Z}^{\geq 0}$.

The zero (0) represents the state of equipment failure, and the state denoted as 1 represents the normal operational state. The units are connected to other elements in the branch in series, and the branches are connected in parallel. The equivalent reliability vector of the system components is computed in the following manner:

$$\mathrm{q}_{1\times \mathrm{n}} = \left|\sum_i^m q_{1i} \quad \sum_i^m q_{2i} \quad \dots \quad \sum_i^m q_{ni}\right| \quad (3)$$

where:

n – number of DERs;

m – number of elements in series in one branch of DER;

λ – DER unavailability.

The power generation in DERs depends on the weather conditions. The weather conditions matrix is a square matrix and it has the same number of states as the units' state matrix. The states limits are previously defined and they differ from case to case.

$$\mathrm{I}_{n\times n} = \begin{vmatrix} p_{\mathrm{I}\to\mathrm{I}} & p_{\mathrm{I}\to\mathrm{II}} & \cdots & p_{\mathrm{I}\to n} \\ p_{\mathrm{II}\to\mathrm{I}} & p_{\mathrm{II}\to\mathrm{II}} & \cdots & p_{\mathrm{II}\to n} \\ \vdots & & \ddots & \vdots \\ p_{n\to\mathrm{I}} & p_{n\to\mathrm{II}} & \cdots & p_{n\to n} \end{vmatrix} \quad (4)$$

The probability of a certain weather condition occurrence depends on the location and it is computed by statistical data analysis. This is one of the major factors for determining DERs placement. In other words, the probability of sunny weather is greater in the Equatorial regions, then in the North.

The total system reliability, which is a product of the components reliability and the states' transitions matrices of the weather conditions and the equipment installed, is shown with equation (7).

$$\mathrm{R} = \mathrm{q}_{1\times n} \cdot \mathrm{A}_{n\times n} \cdot \mathrm{I}_{n\times n} = \\ = \left|\sum_i^m q_{1i} \quad \sum_i^m q_{2i} \quad \dots \quad \sum_i^m q_{ni}\right| \cdot \\ \cdot \begin{vmatrix} a_{0\to 0} & a_{0\to 1} & \cdots & a_{0\to n} \\ a_{1\to 0} & a_{1\to 1} & \cdots & a_{1\to n} \\ \vdots & & \ddots & \vdots \\ a_{n\to 0} & a_{n\to 1} & \cdots & a_{n\to n} \end{vmatrix} \cdot \\ \cdot \begin{vmatrix} p_{I\to I} & p_{I\to II} & \cdots & p_{I\to n} \\ p_{II\to I} & p_{II\to II} & \cdots & p_{II\to n} \\ \vdots & & \ddots & \vdots \\ p_{n\to I} & p_{n\to II} & \cdots & p_{n\to n} \end{vmatrix} = \\ = |\mathrm{r}_1 \quad \mathrm{r}_2 \quad r_3| \quad (5)$$

The result is a row-vector which contains the probability rates of the worst-case scenario, for instance, the probability of sunny weather when PV modules are in operating conditions or the probability of windy weather when wind generators are in working condition.

5. CASE STUDY

The case study analyzes a distribution network with three types of DERs: a PV array, wind generators, and a ROR power plant. The single line diagram of the system is shown in Figure 2 and the unavailability rates of the equipment are shown in Table 1.

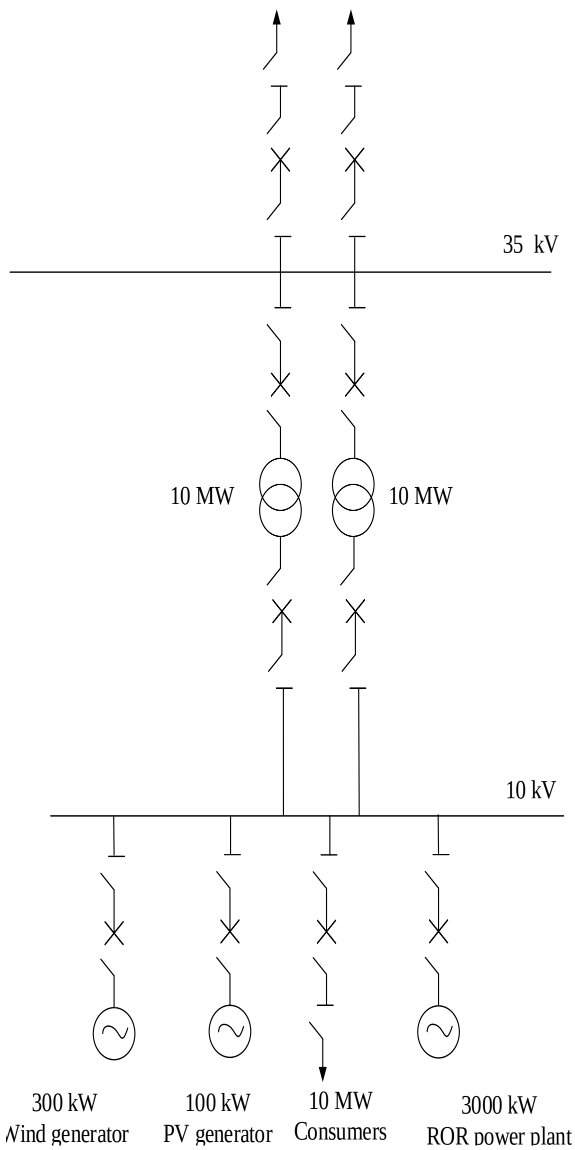

Fig. 2. Distribution network with implemented DERs

Table 1

Unavailability rates of the equipment

Components	Voltage rate kV	Symbol	Unavailability rates
Earth switch	110	u_{ES}	0.00037
Disconnector	110	$u_{D,110}$	0.0029
Circuit breaker (CB)	110	$u_{CB,110}$	0.0038
Bus 110 kV	110	$u_{bus,110}$	0.00017
Power transformer	110/10	u_{TR}	0.0043
Circuit breaker	10	$u_{CB,10}$	0.0032
Disconnector	10	$u_{D,10}$	0.0048
Bus	10	$u_{bus,10}$	0.00011
PV generator	10	u_{pv}	0.028
Wind generator	10	u_{wind}	0.08
Hydro unit	10	u_{hydro}	0.0006

In the first step of applying the proposed method, the equivalent branch unavailability has to be calculated. The probability of failure of the PV array equals to:

$$q_{PV} = u_{pv} + u_{D,10} + u_{CB,10} = 0{,}036 \quad (6)$$

The equivalent unavailability of the wind farm and the ROR power plant are:

$$q_{WIND} = u_{wind} + u_{D,10} + u_{CB,10} = 0{,}088 \quad (7)$$

$$q_{ROR} = u_{hydro} + u_{D,10} + u_{CB,10} = 0{,}0086 \quad (8)$$

The unavailability of the whole substation is calculated using the theory for serial and parallel connected components. Therefore, the substation is divided into parts consisting of serially connected components. The unavailability of the power lines is:

$$U_{PL} = u_{ES} + u_{D,35} + u_{CB,35} = 0{,}0071 \quad (9)$$

Similarly, the unavailability of the transformer branches is:

$$U_{TR} = u_{D,35} + u_{CD,35} + u_{TR} + u_{CB,10} + u_{D,10} = \\ = 0{,}019 \quad (10)$$

Accordingly, the probability of total outage of the substation defines in the following manner:

$$U_{eqv} = {U_{PL}}^2 + U_{bus,35} + {U_{TR}}^2 + U_{bus,10} = \\ = 0{,}000691 \quad (11)$$

The state transition of the substation equipment is presented graphically in Figure 3.

The probability of transition from one state to another represents the failure rate and it is denoted with λ. The repair rate, i.e. the probability of transferring from a state of an outage or a partial outage to the operational mode is denoted with μ.

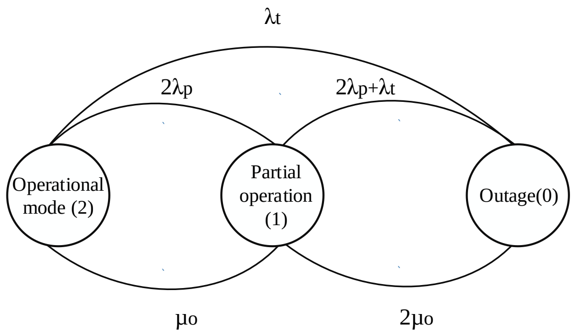

Fig. 3. Markov chain state transition diagram

The system's transition matrix refers to the equipment's probabilities of normal operation, partial operation and outage. The normal operation, denoted as state 2, refers to the availability of the substation equipment for load satisfaction. The partial operation, denoted as state 1, refers to limited power supply due to a failure in some part of the equipment. The state of an outage is denoted with 0.

The system transition matrix for the analyzed case study has the following form:

$$A_{3\times3} = \begin{bmatrix} a_{00} & a_{01} & a_{02} \\ a_{10} & a_{11} & a_{12} \\ a_{20} & a_{21} & a_{22} \end{bmatrix} =$$

$$= \begin{bmatrix} -2\mu_0 & 2\mu_0 & 0 \\ \lambda_p + \lambda_t & -(\lambda_p + \lambda_t + \mu) & \mu_0 \\ \lambda_t & 2\lambda_p & -(2\lambda_p + \lambda_t) \end{bmatrix} =$$

$$= \begin{vmatrix} 0{,}9739 & 0{,}0261 & 0 \\ 0{,}0261 & 0 & 0{,}9739 \\ 0{,}0007 & 0{,}0261 & 0{,}9732 \end{vmatrix} \quad (12)$$

where:

$\lambda_p = U_{PL} + U_{TR}$ denotes the probability of partial operation of the substation,

$\lambda_t = U_{eqv}$ denotes the probability of total outage of the substation,

$\mu_0 = 1 - U_{PL} - U_{TR}$ denotes the repair rate of the substation.

The units' reliability is presented with the reliability row-vector:

$$q_{1\times3} = |0{,}036 \quad 0{,}088 \quad 0{,}0086| \tag{13}$$

The weather transition matrix is calculated by the available weather statistical data for a certain location.

$$\mathrm{I}_{3\times3} = \begin{vmatrix} 0{,}354 & 0{,}107 & 0{,}539 \\ 0{,}359 & 0{,}344 & 0{,}297 \\ 0{,}515 & 0{,}049 & 0{,}437 \end{vmatrix} \tag{14}$$

The total reliability vector is:

$$\mathrm{R} = \mathrm{q}_{1\times3} \cdot \mathrm{A}_{3\times3} \cdot \mathrm{I}_{3\times3} =$$

$$= |0{,}036 \quad 0{,}088 \quad 0{,}0086| \cdot$$

$$\cdot \begin{vmatrix} 0{,}147 & 0{,}590 & 0{,}263 \\ 0{,}238 & 0{,}562 & 0{,}200 \\ 0{,}100 & 0{,}183 & 0{,}717 \end{vmatrix} \cdot$$

$$\cdot \begin{vmatrix} 0{,}354 & 0{,}107 & 0{,}539 \\ 0{,}359 & 0{,}344 & 0{,}297 \\ 0{,}515 & 0{,}049 & 0{,}437 \end{vmatrix} =$$

$$= |0{,}0621 \quad 0{,}0090 \quad 0{,}0616| \tag{15}$$

The row vector presents the probabilities of each DER failure while favourable weather conditions and equipment availability.

ENS is calculated by multiplying the reliability of event occurrence and the total power energy needed:

$$\mathrm{ENS} = R \cdot P_{Load} \cdot T_{year} =$$

$$= |0{,}0621 \quad 0{,}0090 \quad 0{,}0616| \cdot 10 \cdot 8760 =$$

$$= |5438{,}97 \quad 784{,}36 \quad 5392{,}43|\ \mathrm{MWh/year}. \tag{16}$$

The results represent the ENS during an outage of each of the DERs in periods of proper weather conditions for maximum power production and substation outage. The first element refers to the PV array outage, while substation is also in outage and sunny weather. The second element refers to the wind generator outage, during windy weather and substation outage. And the third element represents the ENS to the consumer, while both, the substation and the ROR plant, are in an outage when there are conditions for maximum power generations.

6. CONCLUSION

In this paper, the application of Markov chain model for DERs operation evaluation was presented and mutual dependency of weather conditions and substation equipment was calculated. It were shown that the Markov chain model is an appropriate mathematical method for weather conditions modelling and its usage for DERs reliability estimation is justified.

The presented method gives information for availability of such a system for power supply in both, normal operating conditions and during an outage. It can serve as a base for further development in economic cost-efficiency of DERs projects, considering the weather conditions and operating service of the installed equipment. The future scope of research is to extend the developed model for deeper analysis of the power generation from DERs and make it more effective.

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