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MODELLING OF POWER SYSTEM RELIABILITY ASSESSMENT

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Original scientific paper

The paper presents the way of modelling a subsystem of the power system from the power supply interruption consumer's point. Results of reliability assessment indicate significant differences of results depending on the modelling and understanding of the input data. Valid reliability assessment can be performed only with excellent knowledge of the observed system, organization and rules. As an example of calculation, a simple transformer station 110 / x kV analysis is performed, considering the standard and improved model. The paper gives an overview of the different Markov models for simple transformer station and comparison of the results of reliability and availability. The improved model presented should contribute to better reliability and availability assessment results of observed subsystems.

Keywords: *interface, Markov model, power supply interruption, power system, reliability*

Modeliranje elektroenergetskog sustava za analizu pouzdanosti

Izvorni znanstveni članak

Rad prikazuje način modeliranja podsustava elektroenergetskog sustava s aspekta prekida opskrbe električnom energijom korisnika prijenosne mreže. Rezultati analize pouzdanosti ukazuju na značajnu različitost rezultata ovisno o načinu modeliranja i razumijevanju ulaznih podataka. Kvalitetnu analizu je moguće provesti samo uz vrsno poznavanje promatranog sustava, organizacije i pravila. Za primjer proračuna analizirana je jednostavna trafostanica 110/x kV uzimajući u obzir standardni model i poboljšani model. U radu je dan pregled različitih Markovljevih modela jednostavne trafostanice te usporedba rezultata proračuna pouzdanosti i raspoloživosti. Prikazani poboljšani model bi trebao doprinijeti kvalitetnijim rezultatima analize pouzdanosti i raspoloživosti promatranog podsustava.

Ključne riječi: *Markovljevi modeli, pouzdanost, prekid isporuke električne energije, sučelje, sustav*

1 Introduction

An electric power system is a network of electrical components used to supply, transmit and use electric power. It is possible to divide a power system into the functional units based on technical, economic or other criteria. Reliability assessment of a power system or its functional subsystems can be provided by analytical, simulation, or hybrid methods [12]. Since the reliability calculations are usually complex, for the purpose of the reliability assessment the power system is divided into functional units that are considered as subsystems. Subsystem that can be extracted from the Croatian power system is the interface between the Transmission System Operator (transmission) and Distribution System Operator (distribution). Transformer stations 110/x kV are the interfaces between the transmission and distribution and according to the report on interruptions of power supply, most of the disturbances with supply interruptions occur from that interface. Disturbances that result with power supply interruption within the monitored subsystems are particularly interesting to observe. Taking into account the one-line scheme of the substation in the interface, components of the observed unit and the prescribed procedures in the event of supply interruption, a Markov model for the reliability and availability analysis is made. In addition to standard parameters for reliability assessment, the presented model discusses the parameters that describe the dispatcher procedures at the interface. Condition for applying the Markov state space model is that the parameters are distributed according to an exponential function. However, in some subsystems duration of supply restoration can be represented by another distribution function. In the Markov model failure frequency function and repair frequency function must be independent in time, and the probability density failure function and the probability density repair function have to be exponential function. The application of the Markov model is relatively simple but in the case of a large observed system or subsystem with multiple-state analysis it becomes complicated. The analysis results are very sensitive to the size of the model and input data. Ignorance of the way how data were collected and processed contributes to questionable results. Lately, the reliability indices have been considered within the techno-economic analysis, so it can lead to a bad decision making regarding the power system construction and operation. The Transmission System Operator has an obligation to collect and process data about supply interruption in the transmission network. Since 1994, Transmission System Operator has statistically processed data on operating events of the observed components and units of the transmission network under its jurisdiction, [22].

2 Modelling of components and observed units

Components and units observed for the reliability and availability assessment can be modelled with at least two states. It is assumed that the components used in power system are repairable.

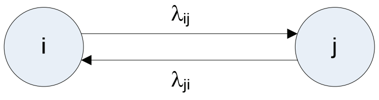

Figure 1 Model of a component with two states (repairable)

Model of a repairable component with two states, functional state and state of failure, is presented in Fig. 1. This model is of course insufficient to describe all the states in which the component can be found. For example, if the component restoration is possible without repairing of the faulty component but only by providing proper switching operations, this means that the observed component is in temporary forced failure. The model of a renewable component which takes into account switching operation is presented in Fig. 2.

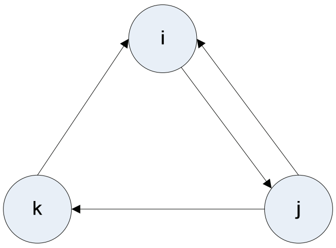

Figure 2 Model of a component respecting switching operation

Figure 2 shows the state diagram of the component where the component from the functional state can change to the state of failure and back to the functional state by repair or providing proper switching operations. In this case, switching operations provide only one parameter which is the total switching time which is often related to the probability of circuit breaker failure, but the details of switching operation performed by operator could not be seen in this model.

3 Markov model "n+2"

During its operating period a component may also be in the state of planned maintenance. To insure that other relevant component states are taken into consideration, the extended Markov model "*n*+2" is applied. The Markov model "*n*+2" can also include switching operations performed by dispatchers [14, 16]. The extended Markov model "*n*+2" is presented in Fig. 3.

State 1 is functional state, such as supply of customers. State 2 marks the state with active failure of component, before fault isolation. State 3 presents the start of the faulty component isolation. X_1 is average duration of collection data about the fault, such as types of protection that was activated, previously measured values of electrical quantities, overview of the status of switching devices and finally decision making about the procedure of the faulty component isolation and supply restoration.

X_k ($k > 1$) is switching time of circuit breakers.

$$X_k = \frac{1}{t_{sk}}. \qquad (1)$$

X_k is average duration of state transition. Those states describe the following states: circuit breaker is in normal open position or it is unavailable (for example, due to SF6 pressure drop).

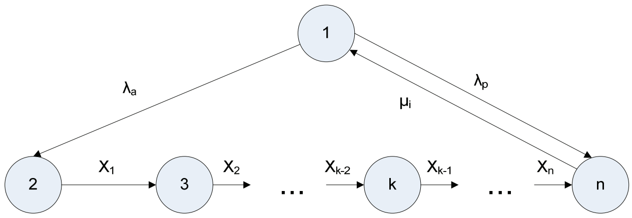

Figure 3 Markov model "*n*+2" [16]

A passive fault is a failure where protection does not activate the circuit breaker, but the faulty component is isolated without supply interruption. For example, if the failure occurs on tap changer on transformer which supplies medium voltage network, the load is switched on the second transformer. Faulty transformer is switched off and repair or replacement of tap changer is done.

3.1 First level event with active fault

Event with active fault takes place when the faulty component is switched off by the circuit breaker activated by protection. For example, active fault is the failure of surge arrester which is in the same protecting zone as the transformer.

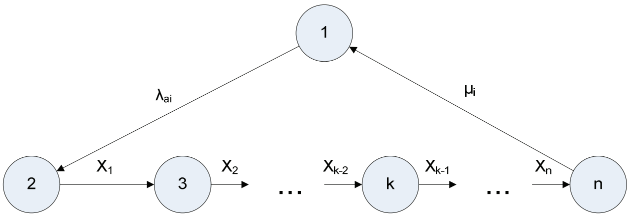

Figure 4 State space diagram for model "*n*+2"with active fault [16]

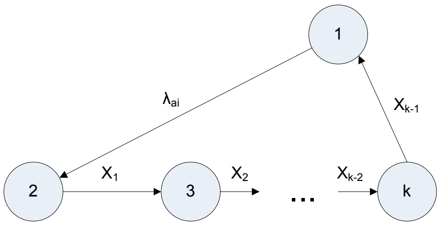

Figure 5 State space diagram for model "*n*+2" with active failure and switching operations [16]

Differential protection of transformers will exclude the transformer and all components within the protecting zone.

In this case faulty component is isolated and there is no need for other switching operations in order to isolate the faulty component. After replacing the surge arrester, the load is switched back on excluded transformer.

Model presented in Fig. 4 describes isolation of component due to fault in unobserved network. In this case there is no repair duration of the faulty component, there is only switching duration for isolation of the unobserved faulty component which caused disconnection of the observed component.

Model shown in Fig. 5 describes a temporary forced fault in which supply restoration is archived by proper switching operations. Component transits from the functional state to the state in failure followed by collection process of the failure data. After that, switching operations are performed and the component transits back to the functional state.

3.2 Event with active fault and failure of circuit breaker

This model considers simultaneously active fault of the component and active failure of the circuit breaker which was supposed to isolate the faulty component. Functional state is the state with both the repaired component and the corresponding circuit breaker.

Simultaneously repairing of both components is modelled because one without the other cannot perform their function. For example, the fault of transformer occurs and protection devices activate the faulty circuit breaker.

Because of failure on circuit breaker, the faulty component could not be isolated. Other protections disconnect all power lines connected to the transformer station. Duration of supply restoration is longer due to the necessity of isolating the faulty component and the corresponding faulty circuit breaker.

State n+3 and n+4 can be described by a single equivalent state, and repair frequency is determined by:

$$\mu_{\mathrm{E}} = \mu_i + \mu_j . \tag{2}$$

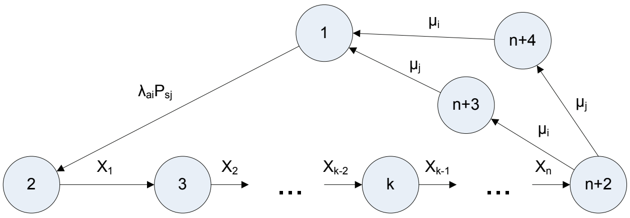

Figure 6 State space diagram for model "n+2" with active failure and component repair [16]

3.3 Event in which one component is under repair and active fault of other component occurs

In this case, due to active failure of the component, the system was transferred from state 1 to state 2. States 3 to n describe the necessary operations in order to isolate and repair the faulty component. Also a transition from state 1 to n is available due to passive fault (protection does not activate the circuit breaker; the faulty component is isolated without supply interruption).

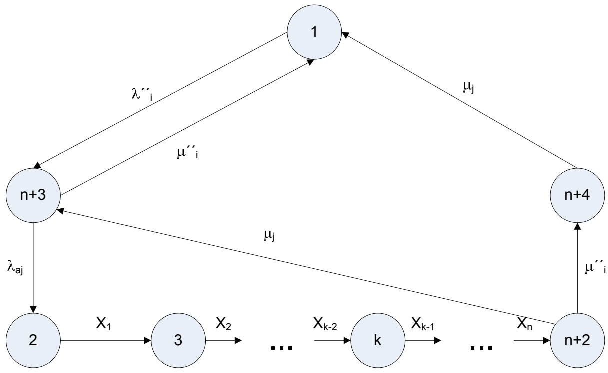

Figure 7 State space diagram for model "n+2" with active failure and planned outage [16]

The repair frequency of components in both cases is the same which is not entirely true. When passive fault is detected, the assessment of the urgency of isolation is performed. It is possible that the component works with the reduced properties till the first planned outage or network topology changes in order to isolate the component without supply interruption.

4 Failure duration of observed component

The observed unit can be found in the forced or planned outage. Characteristic of observed component is event duration. The event starts with a component switching off, and ends with the component switching on. The state duration is determined by the starting and ending time and this is recorded in the statistics of operating events. Another characteristic is a number of events during the observed period. Thus, each observed unit has two characteristics during the observed period: total number of failure (n) and failure duration (T_z). The data in this form often lead to mistakes in the use of the program for reliability assessment.

For the analytical method it is not appropriate if failure rate includes planned outages caused either from observed or unobserved network. The observed unit has an estimated lifetime and the recommendations of the equipment manufacturers for maintenance in accordance to which the Transmission system operator rules of maintenance is formed [16]. It is common to announce the date and the duration of planned outages.

5 Application analysis of the model with switching operations on a typical transformer station

For the analysis of impact of the model with switching operations on reliability indices, two types of one line transformer station schemes are considered. Observed units are determined according to Statistics of operating events with the exception of circuit breakers which are modelled as separated observed components. The parameters of observed component for reliability assessment are determined in literature [1, 2, 5, 6].

5.1 Transformer station with single bus system and one transformer (1S+1T)

According to one line scheme, transformer station has two connected power lines, a single bus system, one transformer and four medium voltage feeders. It is assumed that partial or complete power supply is possible from the medium voltage network. It is assumed that one medium voltage line can supply consumers at medium voltage. Depending on functionality, the components of the primary system are grouped in the observed units as presented in Fig. 8. Customer supply is possible if the following units are in functional state: PJ1 and PJ2 and PJ3 or PJ4 and PJ5, PJ6, PJ7, PJ8 and PJ9.

One line scheme of transformer station is presented in Fig. 8.

If the event when the observed unit is in functional state is marked by x, we can write the following expression for the probability of customer supply in the observed system:

$$P = \left\{ \left(x_1 \cdot x_3 + x_2 \cdot x_4 \right) \cdot x_5 \cdot x_6 \cdot x_7 \cdot x_8 \cdot x_9 \right\}. \tag{3}$$

In order to describe the process of supply restoration, models must be expanded with additional states. Functional state of the observed system is only when all customers are supplied. Due to the complexity of restoration process, the transformer station is divided into three subsystems:

Subsystem 1: Power line bays with associated power lines and circuit breakers (1S +1 T-1)

Subsystem 2: Buses with associated disconnectors (1S +1 T-2)

Subsystem 3: Transformer with associated circuit breaker (1S +1 T-3).

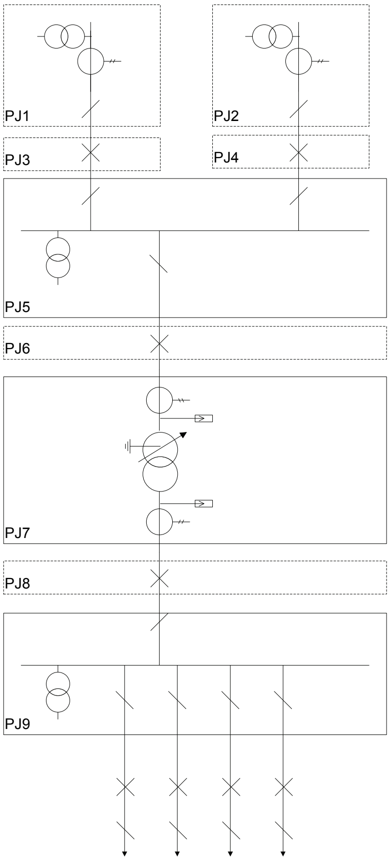

Figure 8 One line scheme of transformer station (1S+1T)

5.2 Subsystem 3: Transformer with associated transformer bay circuit breaker

Consumers could be supplied with electricity from 110 kV network via transformer or through a distribution network from medium voltage lines, of course if such network is developed and able to take over the supply of users. User's electricity supply through transformer station 110/x kV is an initial state (0), while supply from distribution network is reserved for operating state. When a permanent failure of the transformer occurs, supply through medium voltage network (state 4) by operation of internal transformer protection is accessed. During the supply through the distribution network, transformer is being repaired (state 6). After the transformer is repaired, normal operating state is established and customers are again supplied through the transformer station 110/x kV. State (1) describes temporary forced failure. Such a state of the observed components or units occurs where there is no need to repair or replace the observed components or unit but the up state is achieved with the re-switching. In this case, it is important to emphasize that this state can include the effects of internal protection of the transformer, and that is not in down state, for example animals bridge the terminals of the medium voltage transformer. According to the current internal rules transformer diagnostics (sampling, delivery, analysis, findings, and recommendations) should be made. The usual duration of such forced failure is twenty-four hours. The switching procedure is described with the S3 model. Possibility of breaker failure is included in switching on operation, and is shown with the probability of switching on failure where theoretical value can be from 0 to 1. If it is not possible to switch on transformer with breaker, such a state transits in state (3) and then customers are supplied through the medium voltage network. With the simultaneous failure of the transformer and the breaker at the same time, repair of the transformer and breaker is performed as shown in states (6) and (7). Breaker repair time is shorter than transformer repair time. They also take into consideration the planned maintenance of the transformer performed during low load and when its medium voltage network is available.

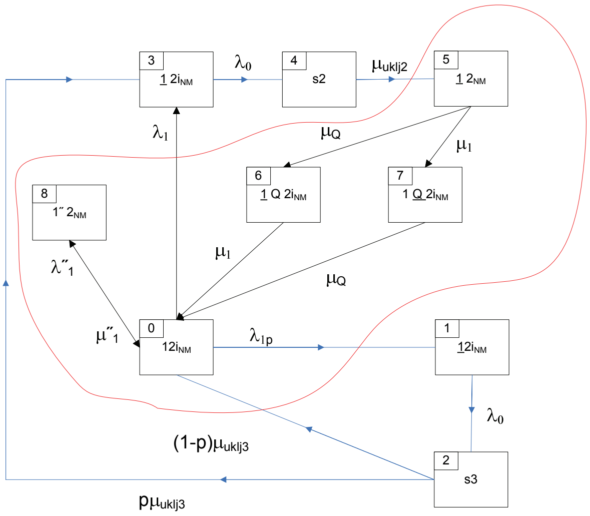

Figure 9 Markov model of subsystem availability (1S+1T-3) [23]

The up states of the subsystem in which undisturbed consumers electricity supply is possible, are (0), (5) and (8).

5.3 Transformer substation reliability (1S+1T)

Unavailability of transformer substation with two transmission line bays, one bus systems and with one transformer is determined by:

$$N(t) = N1(t) + N2(t) + N3(t). \tag{4}$$

Function of availability and the function of unavailability are shown in Fig. 10 and in Fig. 11.

6 Analysis and comparison of calculation results for different models

Reliability assessment of standard model and proposed model is calculated. Standard model for reliability assessment is presented in Fig. 12.

According to the previously defined models for two common schemes of switching substation and operating conditions it is expected to have greater reliability of supply of the switching substation with two transformers, [13, 23]. According to the basic states defined in both models in Tab. 1, comparative reliability indices are shown.

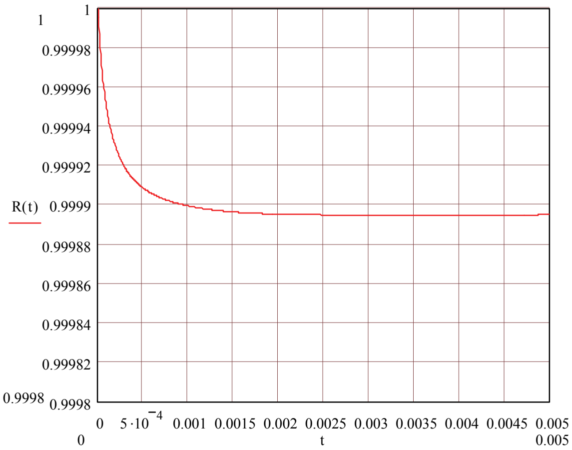

Figure 10 Function of system availability (1S+1T)

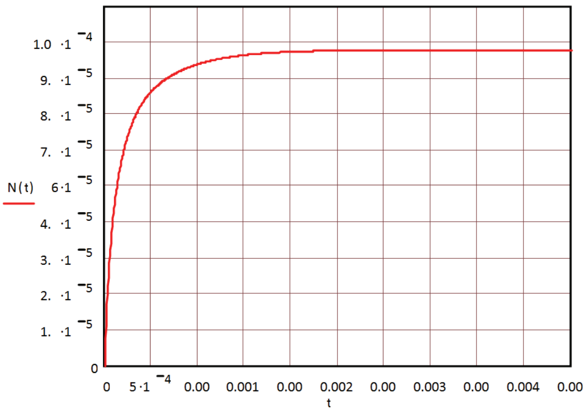

Figure 11 Function of system unavailability (1S+1T)

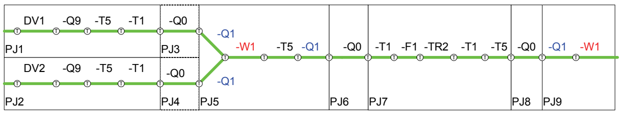

Figure 12 Standard model of transformer station for reliability assessment

Table 1 Comparison of reliability indices

Reliability indices		Model	Standard model
Probability of power supply interruption	P	0,000090971	0,002394478
Expected interruption frequency	f (1/year)	0,99679	1,002400225
Expected interruption duration	r (h/year)	0,80	20,98
Expected interruption duration	r (min/year)	47,81	1258,54
Expected power not served	ΔL (MW/year)	9,968	10,024
Expected energy not served	ΔW (MWh/year)	7,943	210,260

Reliability indices are presented for a substation with a single user for the same single-pole diagram calculated on the basis of different models. The assumption is that the load is constantly equal to 10 MW and depending on the frequency of supply interruption the expected power not served is determined while depending on the expected average duration the expected energy not served is determined. Costs shown for both models should not be taken as the basis for the justification of installation of another transformer. Such decision is influenced also by other parameters, and this is just one indicator.

In the transmission system there are mainly substations with two transformers and the average interruptions duration per substation based on the model has good fit with practical measurements (about 20 minutes) [22].

7 Reliability indices of consumers' nodes

Expected values of reliability indices of consumer nodes (bus) are the measure of severity of the disturbance in which one can expect the power not served (derated power), or expected energy not served, and is therefore also called the expected values of supply interruption. Using the state enumeration method the basic values of the interruptions indices for consumer's node "k" caused by failure "j" to be expected in one year (expected value) are:

The probability of power supply interruption:

$$P_k = \sum_j P_j \cdot P_{kj}. \tag{5}$$

Expected interruption frequency (1/year):

$$f_k = \sum_j f_j \cdot P_{kj}. \tag{6}$$

Expected interruption duration (h/year):

$$r_k = \sum_j r_j \cdot f_j = \sum_j P_{kj} \cdot 8760. \tag{7}$$

Expected power not served (MW/year):

$$\Delta L_k = \sum_j L_{kj} \cdot f_j. \tag{8}$$

Expected energy not served (MW·h/year):

$$\Delta W_k = \sum_j L_{kj} \cdot f_j \cdot r_j = \sum_j L_{kj} \cdot P_{kj} \cdot 8760. \tag{9}$$

Expected interruption costs (kn):

$$C_k = \sum_j L_{kj} \cdot f_j \cdot C_{kj}. \tag{10}$$

Expected interruption costs per MW·h of energy not served (kn/MW·h):

$$C_{kW} = \frac{\sum_j L_{kj} \cdot f_j \cdot C_{kj}}{\sum_j L_{kj} \cdot f_j \cdot r_{kj}}, \tag{11}$$

where:
P_j, f_j, r_j – probability, frequency and duration of forced failure j.
P_{kj} – probability during forced failure j of the node k is greater than maximum power that can be supplied (determined by power flows analysis, $P_{kj} = 0$: there was no supply interruption of consumers k due to the failure j; $P_{kj} = 1$, there was supply interruption of consumers due to the failure "j" regardless of the amount of power and energy not served).
L_{kj} – load curtailed - in node k due to the forced failure j.
C_{kj} – reduction costs in node k due to the forced failure j.

8 Conclusion

Lately, there has been a rising request of future users of electricity for a certain level of reliability at the connection point. Existing software tools for reliability analysis usually cannot model the specificity of the observed subsystem or while performing the analysis it happens that the available data are not understandable so the results of such analysis are often useless because they are contrary to the indicators in practice. For a better understanding and a more accurate calculation a model of substation (usual schemes in the Croatian electric power system) respecting the prescribed procedures for operational staff with disturbance causing supply interruption of customers is made.

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