Proceedings of the Seventh IASTED International Conference
POWER AND ENERGY SYSTEMS
August 29–31, 2007, Palma de Mallorca, Spain
ISBN Hardcopy: 978-0-88986-689-8 / CD: 978-0-88986-690-4

REPRESENTATION OF CORRECTIVE-SWITCHING SEQUENCES BY MARKOV MODELS FOR NETWORK RELIABILITY EVALUATION

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ABSTRACT
A methodology for reliability evaluation of electrical networks by application of extended Markov models is presented. Failure effects which can be relieved by a complex sequence of switching actions are handled by adding additional states to the conventional Markov model. The feasibility of the method will be demonstrated for a real-life industrial-type medium voltage network by assessing the reliability-related effects of different planning concepts for additional supply points.

KEY WORDS
Reliability, Markov models, simulation, corrective-switching.

1. Introduction

Installation of local power generation in distribution networks is not only profitable from economical but also from reliability point of views if power sources are properly located. However, for the assessment of reliability gain attained by operation of local power sources several technical aspects have to be taken into consideration:

- Local power generation leads to an increase of redundancy of supply.

- Overloading of feeders or voltage limit violations occurring in remote network parts during outage situations can be relieved.

- If remote power generation is of the type of emergency generation, starting time delay has to be modeled correctly with respect to corrective switching actions of other type like closing normally open breakers.

Monte-Carlo-Simulation in the time domain [1] is an adequate but computational expensive method to take such operational aspects into account. Advantages of this method are: flexibility, no restriction to special cycle- and outage time distributions, possibility to simulate time series of complex post fault switching actions and to take "time-integrated restrictions" like water or battery storage into account.

Nevertheless, for the evaluations presented in this paper an analytical method basing on Markov-theory [2], [3] was applied since a computer program basing on this method was available [4].

In the paper the following topics will be addressed: Extension of Markov- models for simulation of corrective switching actions with different time delay, an approach to take emergency generation with restricted battery storage into account, extensions of failure effects analysis to handle overload reduction by redistribution of distributed power generation.

The developed models will be applied to an industrial-type medium voltage network in order to find answers to following questions: Should a second connection to another supply point of the high voltage grid be constructed or should loading of the existing cable system be reduced by local generation injected directly into the medium voltage network. If local generation had to be preferred, should it be provided by gas-engine- (diesel-type-) or gas-turbine-units.

2. Markov models with representation of corrective switching

2.1 Basic Model for single outages and single outages overlapping with maintenance

Markov theory is based on exponential distributions. In practice, distributions of that type are well suited for modeling cycle-times but less adequate for outage- and switching-times. However, the shape of time-distributions becomes irrelevant if reliability computation results serve as forecast for a large observation period [3]. Thus, Markov method is adequate for the applications presented in this paper.

For both cases (outages not overlapping and outages overlapping with maintenance) the model structure of Fig. 1 is used but adapted to the special case.

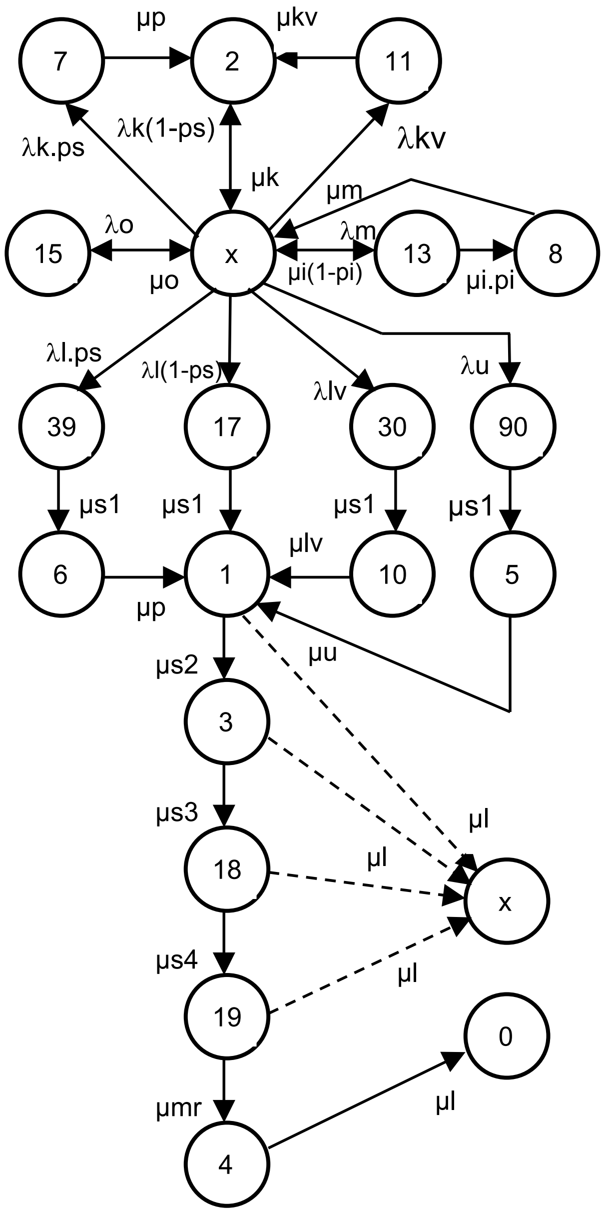

Fig. 1. Markov model for single outages and single outages overlapping with maintenance

2.1.1 Description of states

No 0: normal operation, 1: permanent outage (po), corrective switching with short time delay (csw-s), 2: temporary outage (tmo), successful automatic reclosing without time delay (ar); 3: po, csw- medium delay; 4: interruption of maintenance before finishing works; 5: po, false tripping of protection relay, csw-s; 6: po, failure of 'ar', csw-s; 7: tmo, failure of 'ar'; 8: maintenance; 10: po, protection relay failure to operate, csw-s; 11: tmo, protection relay failure to operate; 13: inspection; 15: operational shut down (performed for other reasons than maintenance; 17: po, successful 'ar', no csw-s; 18: po, csw- large delay; 19: po, csw - very large delay; 30: po, protection relay failure to operate, no csw-s; 39: po, failure of 'ar', no csw-s; 90: po, false tripping of relay, no csw-s.

2.1.2 Transition rates

λl, μl: permanent outage and repair rate; λk μk: temporary outage and repair rate; λlv, λkv: protection system failure-to-operate rates for permanent and transient outages; μlv, μkv: corresponding fault clearing rates (reclosing elements of secondary protection zone); λu, μu: protection system false-tripping rate, corresponding fault clearing rate (reclosing elements without fault location); ps: probability of failure of corrective switching without time delay; μp: rate for reclosing "by hand"; $\mu s1$ to $\mu s4$: rates for corrective switching with time delay (short ($\mu s1$) to very large ($\mu s4$)); μmr: reciprocal of time between maintenance start and interruption; λm, μm: maintenance rates; μi: reciprocal of inspection duration; pi: probability of performing maintenance as a result of inspection findings, λo, μo: operational shut down rates.

The single-outage model serves for the evaluation of forced as well as maintenance outage state probabilities. States 8, 13 and 15 are part of this model. State "x" corresponds to normal operation, state 4 does not exist. In the model for outages overlapping with maintenance, state "x" represents maintenance. States 8, 13 and 15 do not exist since they are already taken into account by the outage model. State 4 now is of relevance provided maintenance interruption is admissible for the considered component. After maintenance interruption solely the faulted component remains in outage state 4. Thus, repair leads to transition from state 4 to normal operation state 0. In both models repair of the failed component is taken into account as indicated by the dashed lines which represent μl-transitions from states 1, 3, 18 and 19 to state "x". Right-hand-side state "x" and state "x" in the middle of the upper part of Fig. 1 are identical. State splitting is performed for illustration purposes.

For purposes of simplification the Markov model has been developed under the assumption that special switching actions performed for isolating faulted components after the events "failure of automatic reclosing" (state 39, 6) and "protection system malfunction" (state 30, 10 and 90, 5 respectively) can be finished within a time larger than "short" but shorter than "medium". Thus, all transitions produced by these switching actions lead to state 1, see transition from state 5 by μu, state 6 by μp and state 10 by μlv. Other switching actions with times larger than "short" are represented by one single path emerging from state 1 by rate $\mu s2$ and ending in state 19 or 4 by rate $\mu s4$ or μmr. Path length is dependent on the possibility of performing switching actions. Thus, the path may end with state 3 or even with state 1. In any case, solely one single μl-transition is possible either from state 1, 3, 18, 19 or 4.

Inspection state 13 is introduced for the purpose of application of a more complex maintenance model with representation of time-dependent degradation of component condition. It was shown in [5] that this model can be reduced to the shape of Fig. 1, state 8 and 13.

For temporary outages no other corrective action than switching without time delay is simulated and false relay tripping is not taken into account.

Models for other outage types like common-mode outages, independent double outages and outages occurring during adverse weather are presented in [6].

Numerical values for input parameters have to be evaluated according to real operating conditions. Outage statistics and operation personnel experience constitute an important information source for parameter estimation. Due to lack of information, in the model used for the calculations presented in chapter 4, protection-system-failure- and inspection-states had to be excluded.

2.2 Modeling of emergency generation with restricted battery storage

Modeling is based on energy considerations. Thus, no special simulation in the time domain is necessary to assess the effect of emergency generation. The amount of not delivered energy of a single outage event which leads to interruption of supply is given by:

$$Ea = Td.Pd \qquad (1)$$

Td interruption duration
Pd interrupted power

If we assume that the emergency generation device is able to deliver its rated power Pe for Te hours then there remains a rest of not delivered energy given by (2)

$$Er = (Td.Pd - Te.Pe) \qquad (2)$$

If the availability of the emergency generation device Ve is taken into account two cases have to be distinguished. In the first one the device is available with not delivered energy given by (2), in the second one the device is not available with not delivered energy given by (1). Summing up these two energy contributions we get expression (3).

$$Ed = (Td.Pd - Te.Pe).Ve + Td.Pd.(1 - Ve) \qquad (3)$$

Multiplication of Ed with outage probability results in the final value for not delivered energy. This simple approach has the drawback that the influence of emergency generation devices is taken into account solely in the not delivered energy as well as in other reliability indices derived from it but not in the time-based indices. Thus, time-based reliability indices represent consumer reliability from network point of view whereas energy-based indices represent reliability from consumer point of view.

2.3 Evaluation of state probabilities

State probabilities can be computed by simple formulae of the type

$$p_B = ps.p_A.\lambda_A/\lambda_B \ . \qquad (4)$$

p_A predecessor state, e.g. state 1, Fig. 1
p_B successor state, e.g. state 3, Fig. 1
λ_A predecessor state transition rate, e.g. μs_2, Fig. 1
λ_B successor state transition rate, e.g. μs_3, Fig. 1
ps probability of failure of corrective switching; 1 if no such failure is taken into account

Since according to Fig. 1 all states are arranged within chains with sources at state "x" respectively 0, they can be expressed by state "x" or 0 applying a back-substitution procedure [4]. Formulae similar to (4) can be applied for computation of transition frequencies [4].

3. Failure effects analysis, simulation of corrective switching and overload handling

The general procedure for failure effects analysis and corrective switching is illustrated by the flow chart of Fig. 2. The procedure results in a value for interrupted load or load reduced by load shedding in order to keep the system within technical limits.

"Set Outage situation" corresponds to a state of the Markov state-space diagram of Fig. 1.

To relieve limit violations not only "corrective switching" can be performed but also adjustment of network-control parameters such as reactive generation, reactive compensation, transformer and phase shifter taps and FACTS- devices settings. For control parameter adjustment, power-flow optimization (OPF) basing on a genetic algorithm (evolution strategy) is applied. Block "corrective switching" represents also generation re-dispatch and load shedding if no sufficient amount of generation is available. The content of this block is described in more detail in [6].

Check for "controlled variables at limits" is performed in order to simulate "remedial actions" in the case that controlled variables (e.g. line currents or voltages) approach to their limits. An example of such an action could be opening a bus-breaker to increase network impedance and redistribute load flows to other parts of the network. Subsequently, additional "corrective switching" actions are simulated to take advantage of the possibility of strengthening the changed network structure by putting spare lines into operation.

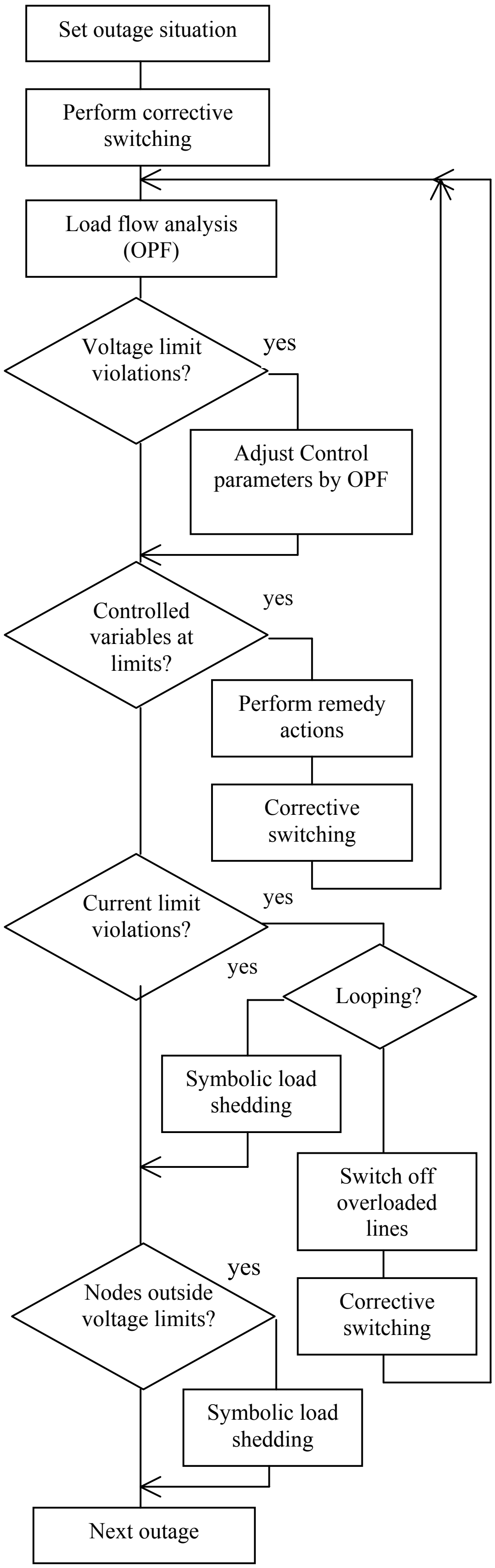

Fig. 2. Failure effects analysis and corrective switching

If prophylactic measures performed to avoid limit violations are not successful then overloaded lines are switched off or load is reduced. In this context "Looping" indicates that current limit violations cannot be removed by switching-off or load shedding. In that case load is symbolically shed in proportion to the amount of limit violations. Failure effects analysis is ended with a last check for "nodes outside voltage limits". If limit violations are detected, symbolic load shedding is performed by a strategy similar to that which is applied to take current limit violations into account in the case of "Looping".

4. Results

4.1 System description

The presented methodology has been applied to an industrial medium voltage network. Fig. 3 shows its simplified structure.

Presently this system is supplied by four parallel cables leading from the high voltage grid to a gas-isolated bus system, left side of Fig. 3. Consumers are supplied by a number of cable-rings. The figure represents one ring for normal and another one for critical consumers. In the case of main supply interruption, critical consumers are isolated from the rest of the grid and a rapidly starting emergency generation unit is put into operation. During the starting-delay-time of the unit consumers are supplied by battery storage devices. A second unit is available for emergency supply of other important consumers.

Due to load increase the present high/medium- voltage connection will loose n-1 security within the next years. To restitute the system back to a secure state the following planning concepts are taken into consideration:

A: Build a second supply point which will be located in another region of the high voltage grid and connect it to the medium voltage bus system by four cables. (In fact, in this variant the new lines will serve as main connection and the old lines as normally open spare connection). For this concept three sub-variants with different switching-in times of the spare connection will be considered, namely A1: 10min, A2: 5min, A3: 3min.

B: Build a local power plant with a minimum of three gas-engine- (diesel-type-) units (concept B1). The capacity of the three units together will correspond to the capacity of one cable. Sub-variants with one additional spare unit (concept B2) and two spare units (concept B3) will also be taken into consideration.

C: Build a local power plant with one (concept C1) or two (concepts C2 and C3) gas-turbines. In concept C2 the second unit serves as reserve for outage situations whereas in concept C3 it will be permanently kept in operation. The capacity of one of these units will be equal to the capacity of one cable line.

Fuel for gas-turbines as well as for gas-engines will be natural gas.

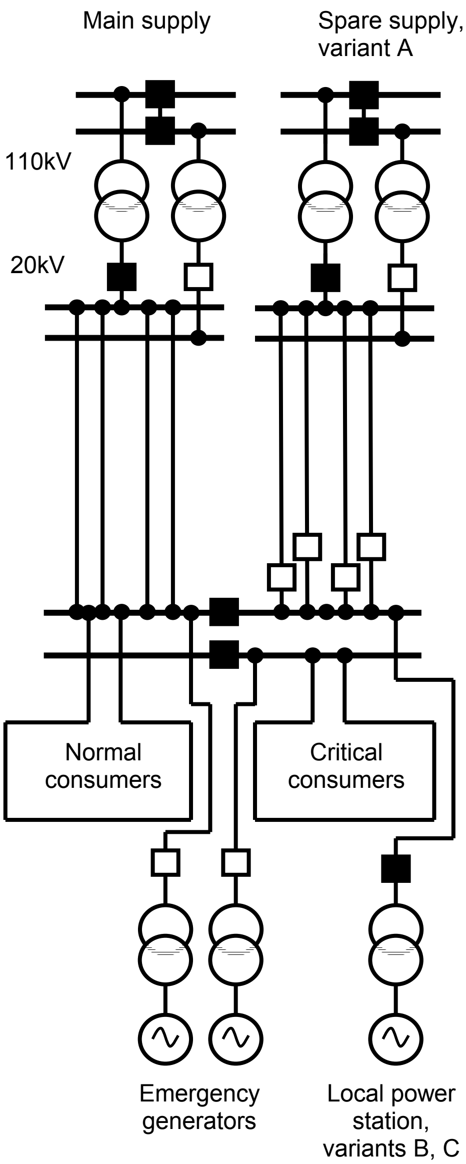

Fig. 3. Study system

At first, two variants for the location of the additional supply point were taken into consideration:

1.) Location at the existing power station, represented by the sectionalized double-bus system (bottom of Fig. 3).
2.) Second power station in a remote part of the medium voltage network.

In expansion plan no.2 the network would have to be split up into two separate parts to suspend short-circuit power flow transfers during the occurrence of faults in the high voltage grid. For that reason plan no.2 was not further taken into consideration.

4.2 Component reliability indices

Component reliability indices are taken from literature, see [3], [7] - [9]. The reliability indices for some devices are given below. (First value: outage frequency; second value: outage duration expectation).

110kV/20kV Transformers: (0.0233/a; 24h), 20kV cables - permanent outage: (0.027/km.a; 30h), 20kV cables common mode double outage: (0.0013/km.a; 40h), generator units: (1/a; 260h), busses (GIS): (0.005/a per section; 48h). No temporary outages are taken into account.

4.3 Comparison of alternatives

In Fig.4 Loss of Load Expectations (= loss of load probability * 8760) for the different concepts are shown. Variants B1 and C1 with local generation cannot concur with concept A - additional cable connection. To reach supply reliabilities in the range of concept A by concepts B and C, additional reserve units have to be allocated. With two additional gas-engine units or one additional permanently spinning gas-turbine, non-reliability can be reduced to a level lower than that of variant A1. However, by reduction of switching time for the spare cable-supply (variants A2, A3), reliability of concept A can be increased to larger values than the best ones of concepts B and C.

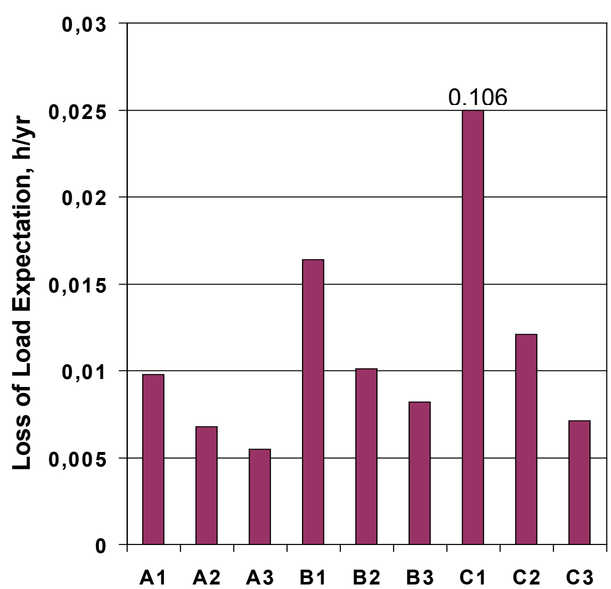

Fig. 4. Loss of Load Expectations for concepts with additional supply

The dominant failure event for concept A is the outage of the supply transformer. Other less dominant events are common-mode double outages of the cable connection and of its terminal busses. Reliability of concept B1 is determined by the same outage situations as concept A. Additional dominant events are combinations of a generation-unit outage with the common-mode double outage of a cable. If spare units are available, the latter events are not critical. Thus, for concepts B2 and B3 the same outage events as for concept A are relevant. Dominant failure events for concept C1 are combinations of an outage of the gas-turbine unit with cable-single-outages and common-mode double outages. For concepts C2 and C3 similar dominant failure events as for concept A exist.

Apart from reliability considerations, economic aspects have to be taken into account for decision finding. For the observed system fuel cost, electricity tariffs and power plant efficiency play a more important role than investment costs. Analysts expect an increase of electricity tariffs as well as of natural gas tariffs within the next years. Furthermore, tariff levels will depend on results of negotiations between network owner and suppliers. Thus, at the moment of finishing this study differences between tariffs could not serve as stringent decision criterion. In accordance with the network owner outage costs were not taken into consideration.

A more relevant criterion is the possibility of utilization of waste heat produced by power plants. Thus, a comparison of heat demand with heat production of variants B and C was performed. It turned out that heat production of three diesel-type units (variant B1) could be consumed during an economically acceptable number of hours per year. This would not be the case for variants C because of the lower efficiency of gas turbines. Thus, gas turbine variants had to be excluded from further considerations.

Although variant B1 would be adequate with respect to waste heat production, it could not concur with variant A with respect to reliability. Since investment costs for the more reliable variants B2 and B3 would be too large, variant A turns out to be the best compromise with respect to cost and reliability.

Nevertheless, taking a gas-engine plant in addition to the second cable connection into operation was not definitively excluded from future planning.

5. Conclusion

A methodology for reliability evaluation of electrical networks by application of extended Markov models was presented. To take corrective switching with different time delay into account, additional states are included into the Markov models. Although less flexible than Monte Carlo simulations in the time domain, this method turned out to be adequate for simulation of failure events which can be relieved by a complex sequence of switching actions.

Feasibility of the method was demonstrated for a real-life industrial-type medium voltage network by assessing its reliability for different alternatives of additional supply like additional cable connections to the supplying high voltage grid or additional local power plants.

Concept "additional cable connection" turned out to be the best one from reliability point of view. A comparable reliability level could be reached by concepts with local power injection if additional spare units were available. However, in that case investment cost and waste heat production would be too large. Thus, variant "additional cable connection" yields the best compromise between cost and reliability.

References

[1] R.Billinton and Wenyuan Li, *Reliability Assessment of Electric Power Systems Using Monte Carlo Methods* (Plenum Press 1994).

[2] R.Billinton and R.N. Allan, *Reliability Evaluation of Power Systems* (Second Edition, Plenum Press 1996).

[3] J. Endrenyi, *Reliability modeling in electric power systems* (John Wiley & Sons, 1978).

[4] G. Theil, M. Theil, Evaluation of reliability indices for high voltage networks with uncertain component reliability data, *Proc. 13th Power Systems Computation Conference*, 1999, 194 - 200.

[5] G. Theil, Markov models for reliability centered maintenance planning, *Proc. 15th Power Systems Computation Conference*, 2005, session "reliability".

[6] G. Theil, Representation of corrective switching with different time delays by Markov- models for reliability evaluation of networks with distributed generation, *Scientific Report FB1/2007*, Institute for Electrical Power Systems and Energy Economics, Technical University Vienna, 2007.

[7] S. Fockens, A.J.M. van Wijk, W.C. Turkenburg, C. Singh, A concise method for calculating expected unserved energy in generating system reliability analysis, *IEEE Transactions on Power systems*, 6(3), 1991, 1085 - 1091.

[8] Zhong Deng, C. Singh, A new approach to reliability evaluation of interconnected power systems including planned outages and frequency calculations, *IEEE Transactions on Power systems*, 7(2), 1992, 734 - 743.

[9] G. Theil, Outage data analysis - The base for high-voltage network reliability assessment, *IEEE Bologna Power Tech 2003*.