Modelling Economic Aspects of Power Network Reliability

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Abstract. The design of a power distribution network topology with regard to the reliability of the network as a whole forms an important requirement of todays electro-centric society. In this paper, we present the details of a power network processes simulation system based on the multi-agent approach. The system performs very fast computations of the flow of energy with network outages modelled according to a real-world situation. During the simulation the system gathers all (global) temporal and economic aspects of each particular outage in a (simulated) period of tens of years. With hundred cycles of such simulation, we obtain realistic information about the strong and weak points of the network providing thus very important data for the topology design decisions regarding the global economic aspects of the network.

Key words: power network reliability; economic modelling of power network; multi-agent system

1 Introduction

The overall reliability of power networks of 10-22 kV, i.e. rather “local” power networks with very different types of “consumers,” ranging from home power consumers, through various engine-facilities to hospitals and large three-shift factories. Each of these facilities has different requirements of the stability of the power supply and also their economic loss in the case of an outage do not even grow linearly with the outage length. The situation is even more complicated in the case of a network with multiple power sources, where the dynamicity of the network topology plays an important role [8, 4].

In the following text, we present a system which evaluates the reliability of the whole network with regard to possible network outages and their economic impacts on the network elements.

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2 Problem Description

There are different kinds of power distribution network reliability simulation methods but we can distinguish two main approaches: analytical and stochastic one [3, ch. 5]. The analytic methods are based on the creation of a reliability model of the network which consists of serial and parallel connections between basic building blocks as network elements. Reliability indicators can then be computed step by step for every node of the reliability network and applied to the corresponding distribution network nodes. The main advantage of these methods is that they are deterministic, mathematically precise and computationally feasible for moderate network models. The main disadvantage is that they operate with a steady network and cannot take dynamic parameters into account. Some of them can also require oversimplification of the network topology to make the computation possible.

On the other hand, stochastic (Monte Carlo) methods [2, 1] are based on a random generation of the specific set of the events taking place in the network according to the given statistical profile of the events (mean value, distribution function, deviation etc.). Therefore the results of the simulation are not deterministically derived from input parameters and the simulation process must be repeated enough to achieve the required level of certainty and precision. The main advantage of this approach is its flexibility and ability to model more complicated phenomena than it is possible with the analytic methods.[3]

The model discussed in this paper is based on the stochastic generation of the events occurring in the network combined with the deterministic modeling of their effects. To make complex behavior modeling possible, the power distribution network is represented with a network of autonomous agents. Every agent knowledge is local to the particular network element. Overall-network effects are modeled by local knowledge interchange between the agents. In this scenario, the main challenge is to correlate the overall sum of local effects of the failure in distant part of the network. The correlation is determined by the global network properties such as the topology and the "reconfiguration capability" (ability to diminish the failure consequences – primarily the financial loss – by changing of the network topology).

The main aim of the model is to determine the weakest point of the network in the sense of the financial loss, not the outage probability and duration. As we argued in the previous paragraph, such a results can not be obtained by the analytical approach. This justifies the usage of a more complicated stochastic model.

[3] "A Monte Carlo simulation can also more easily model complex system behavior such as nonexclusive events, cascading failures, conditional probabilities, and so forth." [3, p. 241]

3 Model Implementation

The model is implemented using the eXAT multi-agent platform. The input data for modelling are (for every node):

– mean time to failure (MTTF)
– time to failure distribution function
– mean time to repair (MTTR)
– time to repair distribution function
– damage function
– peer nodes in initial topology

At the first step, (pseudo)random intervals of the distribution network items failures are generated according to the given MTTF, MTTR and their corresponding distribution functions. We thus obtain a sample timeline of events to occur in the network during the given time period. This is the indeterministic part of the modeling. The other steps are deterministic and reproducible.

The next input parameter is the initial topology of the network. The global network topology is not known to the particular agents, which makes it possible to change the network topology dynamically. The damage function defines the economical loss of an electrical power consumer according to the outage duration.

The simulation input parameters are thus the events timetable, the initial topology and the damage functions. The information about the failure start and stop times and the failing agent name is propagated throughout the network along the power flow direction. Each failure event causes a wave of economic loss records in all the consumer nodes affected by the outage.

The results of each simulation run are summed up by means of statistical analysis. Thus we can determine the overall economic impact of the particular node failures in the given scenario and identify the weakest points of the network not only as to the failure rate but also taking into account the non-local effect of the failures. Such an analysis would be impossible using the traditional failure probability analysis itself and it is the main reason for using the multi-agent system for modeling.

3.1 The eXAT Platform

eXAT [7] is a software platform for multi-agent systems (MAS) implementation written in the Erlang programming language. It contains support for all main MAS components: *agent behavior* is implemented using a finite state machine and the corresponding transition rules, *agent communication* is supported by FIPA-ACL message passing and *agent intelligence* can be implemented using the included ERES library to store agent knowledge base and knowledge production rules. eXAT also includes the tools for ontology description and compilation into source code.

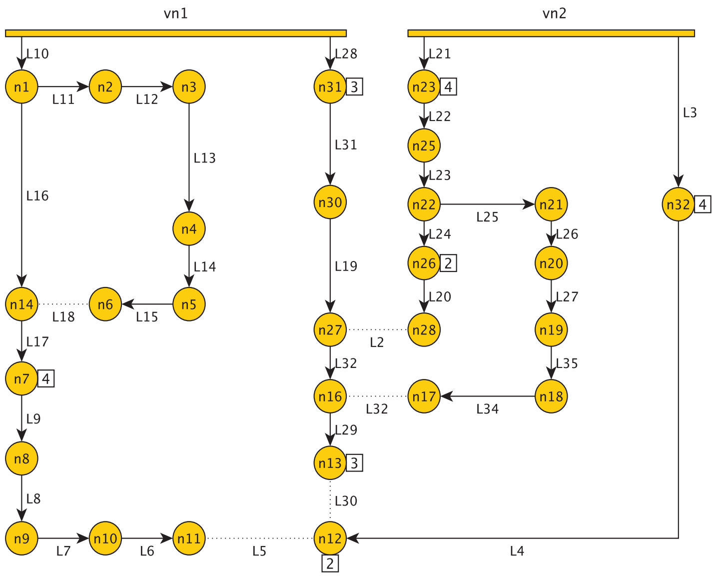

Fig. 1. The modelled network. Most important nodes are marked with a square.

3.2 Agents States

The main part of an agent behavior in eXAT consists of a finite state machine (FSM) and a definition of a transition function. The transitions are triggered by external events: *incoming message*, *knowledge change* or *timeout*.

In the model we consider power network nodes (consumers) failure-free. So the state of the agent representing the node is determined only by the state of its inputs (ok/outage).

An agent representing a power line also maintains its own state (ok/error) and therefore can be in one of four states from which only one leads to a non-outage output state. (The line is in outage if its input is in outage, the line is in error, or both.)

4 The Modelled Network

In this section we will present the results of a modeling of an example power distribution network. The modeled network is based on a real 10 kV utility grid. It consists of 34 lines and 31 nodes thus 65 autonomous agents are used for modeling. The network is fed by two (35/10) kV transformers. The initial network topology can be seen in Figure 1. It is a radial configuration, switched-off power lines are drawn with dotted lines.

All the lines are underground cables with real-world discovered failure rate of

$$\lambda_{line} = 4.85 \; [1/\text{year}/100\,\text{km}]$$

For the purpose of this study, all consumer nodes were classified into three classes as to the economic losses of the consumer in the case of an outage. The damage functions are based on the work [5] and [6].

In Figure 1, the most economically significant nodes (nodes with the most increasing damage function) are marked with a square.

4.1 The Simulation Results

In the stochastic part of the simulation we have used the MTTF value presented in the previous section with the normal distribution and

$$\sigma = 0.1 * MTTF$$

MTTR was constant for all the lines – 18.8 hours with the same distribution as MTTF. We have simulated a 40 years long period of time and the simulation process was repeated for one hundred times.

Basic result statistics are shown in Table 1. There were 33 977 node outage incidents. The mean overall loss computed was 38.6 million EUR. The standard deviation of the overall loss value of distinct simulation runs was under 3% of the mean which signalizes this number does not oscillate much between the particular runs. The overall outage time observed was 6 380 hours. In this number the outage time is computed on affected-node basis thus one hour outage with two affected nodes is counted as two overall outage hours.

The most important aim of the simulation is to determine the overall economic effect of the particular distribution network element failures. The simulation propagates the information about the failure root cause through the network to all affected nodes. When the outage is cleared, each node saves the data about its failure effect to the database. After the run the overall economic damage caused by the particular line error is computed and a ranking of the weakest point of the network (from economic point of view) is processed. Because the economic damage caused by the particular network element failure is affected by the actual network topology and the damage function of all affected nodes, the relationship between the outage hours caused by the particular failures and their economic effect is not linear.

To determine the most expensive (as to the damage caused) and weakest (most damaged) points of the network we make a rank for every simulation run and a statistics of the highest ranked network item. The line 28 was identified as the most failure-expensive item. The highest losses were on the node 13. Both

Table 1. Basic statistics

Value	Mean	Std.deviation
Outages	33 977	
Loss (EUR)	38 614 574	1 043 160
Outage time (h)	6 380	133

conclusions are very strong – the first one was discovered in 91% of the simulation runs, the second in all the runs.

5 Conclusion

We have presented the usage of the multi-agent platform eXAT for the power distribution network simulation. The model consists of a non-deterministic part generating the failure events and the multi-agent system computing the effects of a failures. The post-hoc statistical analysis makes it possible to deduce very important conclusions regarding the global effect of the local network items failures.

Unlike the traditional analytic methods, the stochastic-backed multi-agent approach is highly flexible. The eXAT agent rationality definition system can be used for modeling of even highly dynamic ad-hoc behavior.

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