Evaluation of Generation System Reliability using GRA Computer Program

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Abstract: Reliability is one of the most important criteria which must be taken into consideration during planning and operation phases of a power system even (or may be, particularly) in the time of disintegration, deregulation and competition.

This paper considers the assessment of generating capacity reliability, in terms of adequacy; computationally efficient algorithms and theirs computer realization (GRA program) as well as the case of Polish power system.

The GRA (Generating Reliability Assessment) computer program main features are listed and the utilization of the GRA program in Polish power system studies is illustrated.
Key-Words: Reliability, generation adequacy assessment, software tool.
CSCC'99 Proceedings: - Pages 6191-6196

1. Introduction

The reliability of the electric power system (EPS) is defined by its ability to secure the supply of electricity of acceptable quality to the customers. The reliability of subsystems, constituting the EPS, i.e. generation, transmission, distribution, can be analyzed separately, so the reliability of the achievement of single function: generation, transmission, distribution and supply to particular customers. Three hierarchical levels can be also distinguished in the system [2]:

- HL I, containing the equipment and units generating electricity;
- HL II, containing both the units and equipment for generation and transmission of electricity;
- HL III, containing whole system, including distribution.

After 1990 deep structural changes occurred and still occur in the Polish electric power system; take place disintegration, deregulation and advancing market orientation. This is also a worldwide trend. Departure from the vertically integrated structures, deregulation and market solutions in electric industry create new conditions in which the responsibility for the satisfaction of power demands of individual customers is not and can not be attributed to the particular electric power company. The objective of the electric power system, which is the assurance of electricity supply of the required quality to the customers at the possibly lowest cost and acceptable reliability of delivery is now the task decomposed into many elements and into many subjects.

Reliability is one of the most important criteria, which must be taken into consideration during planning and operation phases of a power system. Electric power sector almost all over the world is undergoing considerable change in regard to structure, operation and regulation. But from a reliability point of view in this “new era”, methods, algorithms and computer software capable of assessing at least the adequacy of systems much larger than in the past are needed [6].

2. Generation reliability

At the first hierarchical level of the EPS the reliability of so-called simplified electric power system is analyzed. The grid of this system does not introduce restriction, at normal and repair conditions, in the use of the available capacity of generation centers for the supply of customer units. So, the reliability of such system is **the reliability of electricity generation in EPS**, interpreted as the readiness of the electric power stations to cover the loads (**adequacy**) [3-5].

The necessity of adjustment of generation capacity for the needs of customers gives more importance for the evaluation of generation reliability in the future, its forecasting. The knowledge of anticipated reliability indices is the basis for the determination of the required capacity (power) reserve in EPS allowing for the coverage of the expected system load (customers demand together with grid losses) and for the performance of preventive and emergency repairs of the generating units.

The historical criteria of deterministic assessment of the reliability of electricity generation were: capacity reserve equal to: determined percentage of the expected load, capacity of one or several biggest units, combination of two preceding options. They are now more and more frequently being replaced by the probabilistic criteria, the fulfillment of which is decided on the basis of the value of particular indices. The most often used reliability indices of electric power system at the level HL I are: LOLP, LOLE, EENS/LOEE/EUE, EIR. The oldest and the most fundamental index - LOLP has the spectacular success. It is used in the formulation of electricity tariffs based on marginal costs. The LOLP is also the element in the settlement of the price of electricity purchase from generators in England & Wales pool and in the system bid market of electricity (SOREE) in Poland.

The reliability of electricity generation can be analyzed as a problem of surpassing by the stochastic process of power demand (load) Z(t) of the stochastic process of generation capacity P(t). The model of the generation reliability consists the stochastic process of power deficit D(t), described as:

$$D(t) = \begin{cases} Z(t) - P(t), & \text{for } Z(t) > P(t) \\ 0, & \text{for } Z(t) \le P(t) \end{cases} \quad (1)$$

The parameters of this process are the quantitative characteristics of generation reliability. It may be those listed above and others.

Generating capacity adequacy assessment involves the creation of a capacity model and the convolution of this model with a suitable load model. In this work, a distribution function of available capacity was used as the capacity model. This function was evaluated by methods:

- recursive (recurrent),
- simulation,
- normal distribution approximation,
- Edgeworth's series approximation.

They were chosen because theirs applicability for both two- and multi-state models of generating units.

3. Computer program for generating reliability assessment (GRA)

The software (GRA program) for the determination of distribution function of available capacity of the EPS and the generation reliability was elaborated.

The subject range of the software includes generation subsystems consisting in two- and (or) multi-state generating units (number of states can not exceed 4), compiled in groups of the identical units. Number of groups and overall number of generating units in the system is limited only by the computer memory because the program evaluates resources and informs user on the resulting possibilities. The program enables to determine distribution function of available capacity (by the listed above methods) and to calculate the following reliability indices of electricity generation:

- LOLE - expected time of capacity deficit in the analyzed period;
- $LOLP_s$ - probability of demand not covered, with the assumption that the load is stable and equal to the peak value - program enables also calculation of LOLP index for each value of load (not only the peak one);
- LOEE/EENS/EUE - expected quantity of not supplied/served energy;
- EIR - power assurance index (Energy Index of Reliability);
- ECD - expected value of capacity deficit;
- PCD - probability of capacity deficit;
- XLOL - expected value of single capacity deficit.

The system load (daily, weekly, monthly or annual) can be considered as:

- step, given in the marginal case by the values for every hour or half-of-hour (which corresponds to the practice of settlements in British pool and includes near future solutions in Poland);
- approximated by the function (application for the load duration curves) - exponential model of load or by polynomial of the 5^{th} order (possibility of arbitrary choice representations of load profiles).

For the system containing no more than 12 generating units (blocks) the GRA program automatically selects the values of capacity (power) for which the distribution functions will be calculated; for larger number of units the user of the program has to specify the step of calculation of distribution function. To get the precise results by the recursive method it is recommended to use the step of calculations equal to the highest common factor of the capacities of the individual units.

The additional features of GRA program are:

- programming language Turbo Pascal v. 7.0;
- legible method of system data recording by the introduction of identifier of group of units (generating units);
- flexible mode of introduction of load data: data prepared outside the program can be used or one can use the patterns in which the typical load profiles in relative units (i.e. as the per unit load levels) are modeled;
- additional options of the elimination of small ("zero") values and the values repeatable in the table of distribution functions of available capacity (the results of exact method - recursive method, are used here);

- convenient way of presentation of the diagrams of distribution function of available capacity (the possibility of presentation of several profiles at one plot and the selection of capacity range - „window") and load (higher resolution);
- possibility of export in the Excel format *.csv of the resulting table of distribution functions of available capacity, of the table of generation reliability indices and the table of LOLP values;
- the possibility of preparation of system data and the load forecast outside the program and their input in the Excel format *.csv.

The GRA program is the convenient and flexible tool for the assessment of the reliability of generation subsystem on the basis of whole set of indices, with the possibility of taking into account the multi-state reliability models of generating units. This will be shown on the example of IEEE test system RTS (Reliability Test System) [1].

The calculations of generation reliability in the RTS system were performed for the period of 24 hours, while this was the day of peak demand in the year, and for the 51st week of the year. The results of calculations are listed in Tables 1 and presented in Figures 1 and 2.

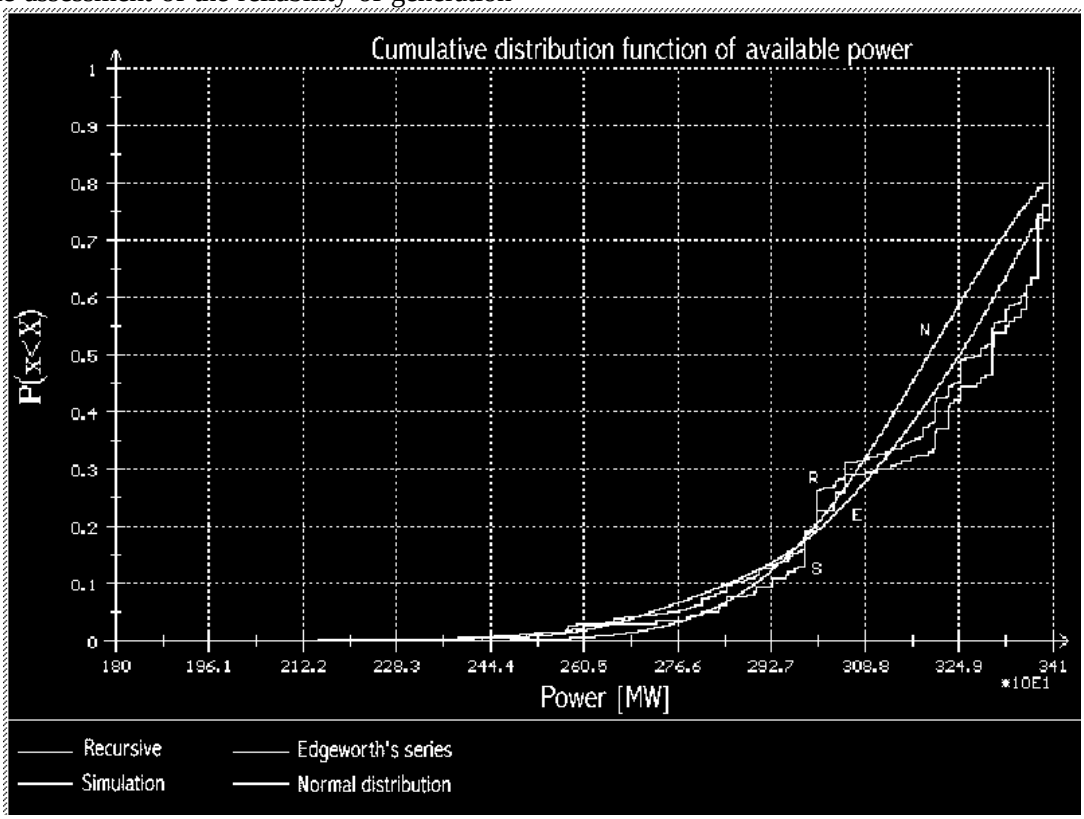

Fig. 1. Distribution function of available capacity of the RTS system in the 51st week, evaluated by different methods (the recursive method is the exact method)

Table 1. Generation reliability indices in the RTS system at the day of highest demand and the time of calculation of distribution function of system available capacity with the use of different methods on IBM AT 486 (100 MHz)

Calculated index	Method used for determination of distribution function Of available capacity			
	recursive	Simulation	Edgeworth	normal distr.
LOLE [h]	**0.6767**	0.73	0.7159	0.3584
$LOLP_S$	**0.08457806**	0.08	0.09816417	0.06738859
LOEE [MW·h]	**102.641**	110.652	96.579	33.273
EIR	**0.99819204**	0.99805093	0.99829883	0.99941392
ECD [MW]	**4.277**	4.611	4.024	1.386
PCD	**0.027227884**	0.02916667	0.02973391	0.0148477
XLOL [MW]	**156.778**	158.075	135.338	93.372
Comput. time [s]	**4.18**	172.41	2.25	0.11

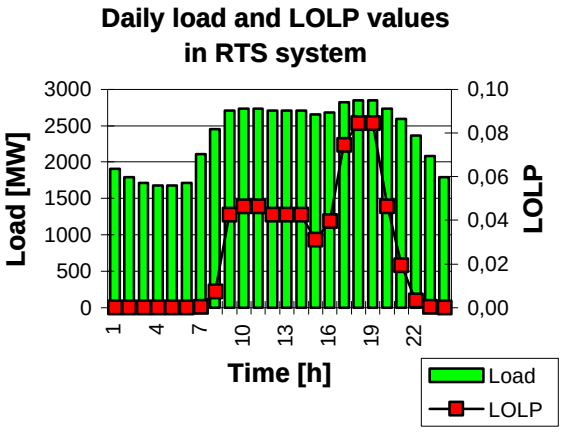

Fig. 2. Daily load profile of RTS system and the calculated values of LOLP with the use of GRA program at the day of highest demand (Tuesday, 51st week of the year)

The computational tests of the GRA program performed for many, with different size, generating subsystems fully confirmed its effectiveness and flexibility. In relation to the used methods of determination of available capacity distribution function it may be stated that:

- the fastest is the normal distribution method, but in reality the distribution of available capacity may differ a lot, especially for the small number of generating units;
- the exact recursive method should be used for small and medium systems and when there is no limit for computation time;
- the Edgeworth's series method fails for small systems, but is correct and fast for large systems;
- the simulation method gives sufficient accuracy but is less effective.

4. Case studies

4.1. Generation reliability of Polish electric power system (PEPS) in perspective

The calculations (within "Tariff study for the Polish electric power industry") were performed for the years: 1996, 1999, 2001, 2003, 2006. For those years the required data concerning the generating units and demand for two limiting scenarios of generation system development: bottom ("D") and top ("G"); were collected and prepared.

The results, with respect to the generating units, constitute the lists of units and their data for every year included in the analysis. It must be stated that some aggregation was made:

- for generating units in thermal block plants:
  - existing units,
  - new units;
- for remaining part of generation subsystem:
  - CHP plants and small commercial power plants in the division into 12 regions - 12 or more (depending on the type of fuel) aggregates;
  - existing industrial power plants and CHP plants - as 1 aggregate;
  - new industrial power plants and CHP - as one aggregate;
  - pumped-storage power plants - as one aggregate;
  - river hydroelectric power plants - as one aggregate.

For every substitute aggregate were given:

- number of units composing the aggregate,
- unit achievable capacity ($P_{os,bl}$),
- forced outage rate (FOR),
- data concerning the planned maintenance in the form of average available capacity at individual quarters of the year and in the whole year (average from four quarters), after taking into consideration the planned protective measures (in % of achievable capacity). These values correspond to the index 1-SOF (SOF is planned maintenance index).

The FOR and SOF values were used for the calculation of the substitute probabilities of availability.

Data concerning demand forecasts were obtained with the use of „Curves" program, used in the Polish Power Grid Company (PPGC) Development Office. For every analyzed year the six files were created.

The calculations of electricity generation reliability in PEPS were performed for annual and daily periods (days with maximum and minimum demand in evening peak), with and without taking into consideration demand for pumping in pumped-storage power plants. This meant the performance of 60 calculation loops (12 for every year). For the determination of available capacity distribution function the recursive (exact) method was used with the step of calculations equal to 5 MW. Additionally, the calculations were performed for annual periods, depicting the influence of failure of realization of development program of generation sources on the generation reliability (bottom scenario of development program - top scenario of demand increase), which indicated next 10 calculation cycles (2 for every year). In this case also the recursive method was used for the determination of distribution function of the available capacity, but with the larger step of calculations - 10 MW.

It follows from the performed calculations that:

- anticipated electricity generation reliability in PEPS is high which is the result of large surplus of achievable capacity of the generating units above the peak demand (high margin of achievable capacity - in variant „D" of development more than 33% and practically constant in the analyzed years, in variant „G" decreasing from almost 37% in 1999 to slightly below 22% in 2006). Only in the year 2006, with the top development scenario, the expected generation reliability falls down and reaches the values: annual expected time of not covering the demand (LOLE) - slightly above 9 hours, the expected annual quantity of not supplied energy (LOEE) - slightly above 7 GW·h;
- the influence of not realizing the development program of generation sources or not enough accurate estimations of demand for generation reliability (bottom variant of development program - top scenario of the increase of demand) is essential because it causes clear deterioration of reliability indices - 3-10 times, but only for the year 2006 these values are alarming: the annual expected time of not covering the demand (LOLE) - about 26.5 hours, the expected annual quantity of not supplied energy (LOEE) - about 23.6 GW·h;
- the influence of consumption on pumping in pumped-storage power plants on the generation reliability in annual perspective is negligible;
- with the assumed method of projection of planned maintenance there is no distinct influence of their timetable on generation reliability on the characteristic days - maximum and minimum demand in evening peak - at the existing margin of achievable capacity and the used in practice timetable of repairs during the year the seasonal variability of generation reliability is decided by the seasonal variability of demand;
- the change of step of calculations in the determination of distribution function of available capacity (from 5 to 10 MW) applied in the study of the influence of not realizing the development program of generation sources or not enough estimation of the forecast for the generation reliability did not have essential influence on accuracy.

4.2. LOLP at Polish system bid electricity market (pool - SOREE)

The above calculations were performed for the whole PEPS. In the near future in Poland the electricity markets will be in operation - the system bid electricity market and regional markets. The analysis of generation reliability in the division for these markets is currently difficult due to the lack of possibility of determination of forecasts of demand in regional markets and in SOREE. All calculations require making the arbitrary assumptions and their results should be treated carefully enough. Despite of all mentioned above limitations is possible to use the GRA computer program for analyses in this new "market" situation. This will be shown on the example of system bid electricity market.

For the purpose of calculations of generation reliability at SOREE (including the probability of not covering the demand) every offer for generation submitted by the generating units of the bid market (JWRO) would be characterized by:

- upper limit of control range - maximum offered capacity - P^{max},
- probability 1-FOR,
- probability $1-P_{nr}$ (where P_{nr} - probability of „unsuccessful" start-up of the unit, at the shortage of reliable data it can be assumed to be equal to 1-FOR or to the availability index AF).

To perform calculations there are necessary:

- fixed data (for example for the given year) for every JWRO: 1-FOR, $1-P_{nr}$;
- forecast of demand in PEPS together with the required rotating reserve;
- offers of the individual generating units participating in SOREE;
- generation plan of the external sources (at local markets, pumped-storage power plants and the international exchange);
- plan of JWROs operation in the previous planning horizon.

As an example the hypothetical situation was considered when all JWROs submitted the maximum offer of production, constant for the whole settlement day and the expected pool load changes in the same way as the load of PEPS at the day of maximum demand in evening peak (in 1996). As a reliability parameters of generating units their availability indices AF (average from the years 1993-95) were used. The maximum capacities of JWROs - P^{max}, also were assumed as achievable capacities from Dispatching Center data.

The results of calculations of the LOLP index and the unit offer price (JCO), for the case when the margin of pool offered capacity in the peak of demand is equal to 30% (peak load equal to 13500 MW) are shown in Figure 3. JCO is Polish equivalent of capacity payment (JCO = LOLP×KNZ, with KNZ = 1450).

The calculations were performed with the assumption that SOREE (pool) has the objective to cover the country demand not covered by the so called „external generation", i.e. the units with power

out-comes at 110 kV, hydro-units, collector power plants and CHP plants.

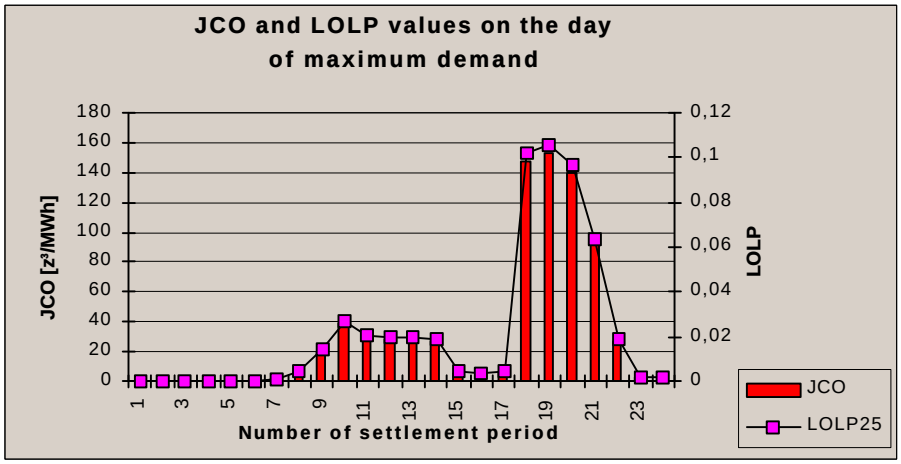

Fig. 3. Values of unit offer price (JCO) and the Loss of Load Probability (LOLP) for the hypothetical case when capacity margin SOREE in the peak of load is equal to 30% (peak load equal to 13500 MW)

It should be added that in the practical cases would exist the dependence not only on the value of capacity margin but also on the contents of the offer (which JWROs will submit the generation offers).

5. Conclusions

An implementation of the methodology of generation reliability assessment is presented in this paper. From many methods for evaluation of available capacity distribution the four methods (recursive, simulation, normal distribution, expansion in Edgeworth's series) were chosen and implemented in software tool - the GRA computer program. At least three of them (recursive, normal distribution, Edgeworth's series) have confirmed their computational effectiveness.

The GRA program is the convenient and flexible tool for the assessment of the reliability of generation subsystem on the basis of whole set of indices, with the possibility of taking into account the multi-state reliability models of generating units. This was shown on the example of IEEE test system RTS and during calculations performed for the Polish power system.

In the near future in Poland, when the electricity markets will be in operation - the system bid electricity market and regional markets, the analysis of generation reliability for these markets should be done.

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