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Research Article

RELIABILITY INVESTIGATION OF ELECTRICAL POWER SYSTEM

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ABSTRACT

The principles of evaluation of the reliability of electric power generation in a power system including thermal and wind power plants are considered in this paper. Besides classical probabilistic models the use of uncertain probabilistic and fuzzy probabilistic models of reliability is recommended. Generation of electric power at wind power plants is treated as a non-stationary stochastic process controllable only to down. The paper presents numerical examples.

INTRODUCTION

Electrical power systems are very complex and highly integrated. Failure in any part of the system can cause interruptions of supply to end users. Power system reliability is increasingly a concern to the power industry and society at large. At present, power system operations are to be handled in a heterogeneous environment. Generally, reliability analysis is being carried out during planning stage of power system operations

The primary function of a power system is to supply its customers with electrical energy as economically as possible with acceptable reliability and quality. Power system reliability is defined as the ability of the system to satisfy the customer demand. Demands for electric power with high reliability and quality have increased tremendously in the past few decades due to the digital revolution. It is expected that the requirements for high quality, reliable power supply will continue to increase in the immediate future. Customers such as commercial, industrial and residential users expect a highly reliable supply with relatively low rates. The electric power industry throughout the world is undergoing considerable changes in information systems, and Web enabled service oriented architectural models are emerging to support the integration of different power system applications. The evolving changes in power system planning and operation needs require a distributed control center that is decentralized, integrated, flexible, and open. As the markets expand and the power grid becomes more congested, operational reliability is becoming more crucial. Maintaining system reliability requires more robust data acquisition, better analysis and faster coordinated controls. The practice of interconnecting individual power systems into large grids has resulted in economies in capital and operating expenses as well as improved reliability (Ewart and Kirchmayer 1971). The full exploitation of these benefits presents an increasingly complex problem to the power system operator; consequently, the electric utility industry is devoting greater effort to the application of automation technology to the solution of system operating problems. The relevant developments in automation technology are associated with analog and digital computers, data collection and supervisory control equipment, communication devices, and displays. The computers are being applied on a time-shared basis as a valuable tool in solving the problems of power system planning, operations control, and operations accounting, all of which involve both economic and reliability considerations.

Reliability is a fundamental requirement put to the power systems and their subsystems. Different probabilistic models are used for evaluation of the reliability of power systems. Yet

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the probabilistic models are not sufficiently general for reliability evaluation. In a power system the failures take place relatively seldom, and the failure-repair cycle changes in very large limits. The questions when a failure occurs and how long it will take to repair are rather uncertain or fuzzy events than probabilistic cases. Therefore also the perspectives of using the uncertain and fuzzy models for evaluation of the power system reliability are studied. In this paper we will introduce the probability, uncertain probability and fuzzy probability models of reliability and their applications for the analysis of electric power generation reliability. The paper is based on reliability studies of oil shale power plants and units. The output power of wind power plants is treated as a non-stationary random process. Their reliability from the classical point of view is very low. Some special characteristics are used for describing the availabilities of wind power plants.

Bulk Power System Reliability

An electric power system is generally composed of three parts: (1) generation, (2) transmission, and (3) distribution systems, all of which contribute to the production and transportation of electric energy to consumers. The reliability of an electric power system is defined as the probability that the power system will perform the function of delivering electric energy to consumers on a continuous basis and with acceptable service quality.

At the present stage of development, the reliability evaluation of the entire power system (HL3) is usually not conducted because of the immensity and complexity of the problem in a practical system. Instead, power system reliability is assessed separately for the generation system (HL1), the bulk power system (HL2), and the distribution system. Reliability analysis methods for generation and distribution systems are well developed due to difficulties arising from the huge computational burden associated with the bulk power system reliability analysis. Thus, this research concentrates on the area of bulk power system reliability assessment.

Power System Reliability Concepts

Electricity is a basic commodity that drives the economic productivity and prosperity of a society. Modern electrical power systems have the responsibility of providing a reliable and economic supply of electrical energy to their customers. The economic and social effects of loss of electric service can have significant impacts on both the utility supplying electric energy and the end users of the service. Maintaining a reliable power supply is therefore a very important issue in power system design and operation. Reliability of a power system is generally designated as a measure of the ability of the system to provide customers with adequate supply. It is one of the primary performance criteria of power systems. Major outages can have a significant economic impact on end users as well as power utilities. Power system has been significantly affected by a wide range of outage events caused by incorrect planning, operational error, equipment failures, environmental conditions, adverse weather effects, and load conditions. Large-scale blackouts are emphasizing the importance of reliability issues. Reliability is one of the major factors for planning, design, operation, and maintenance of electric power systems. These functional areas are generation, transmission and distribution. The function of the generation system is to make sure that enough capacity is available to meet the load / demand at any time.

It becomes traditional (Billinton and Satish Jonnavithula 1996) within the field of power system reliability evaluation to divide the power system into three functional zones: generation, transmission, and distribution. The three functional zones can be combined to form hierarchical levels. It has been convenient to do so because utilities have traditionally been divided into these functional zones for purposes of organization, planning, operations and / or analysis. Although deregulation has affected the disaggregation of the traditional utility into many separated organizations, most of these organizations still have these corresponding internal divisions or are solely dedicated to the oversight of one of these functional zones. The main purpose of the functional zone division, in terms of reliability evaluation, is to provide a succinct means for identifying the part of the power system being analyzed. Figure 1 shows an organization of the functional zones in hierarchical levels, where the levels increase according to analysis complexity. In a hierarchical level I (HL-I) study, the total system generation including interconnected assistance is examined to determine its adequacy to meet the total system load demand. Reliability assessment at HL-I is normally defined as generating capacity adequacy evaluation. The transmission network and the distribution facilities are not included in an assessment at the HL-I level. Adequacy evaluation at hierarchical level II (HL-II) includes both the generation and transmission in an assessment of the integrated ability of the composite system to deliver energy to the bulk supply points. This analysis is usually termed as composite system reliability evaluation (or bulk power system reliability evaluation).

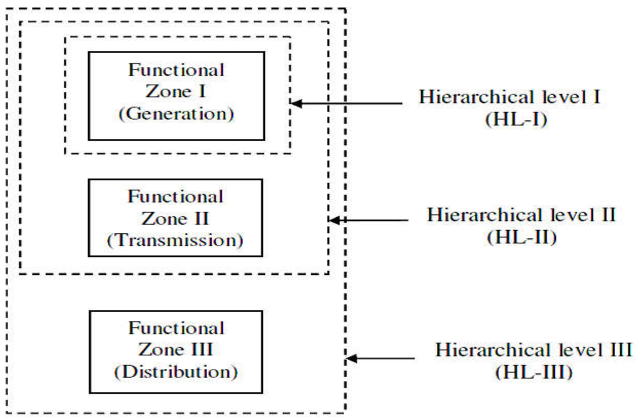

Figure 1 Hierarchical Levels of Power System Functional Zones

Adequacy assessment at hierarchical level III (HL-III) includes all of the three functional zones and is not easily conducted in a practical system due to the computational complexity and scale of the problem. These analyses are usually performed only in the distribution functional zone.

Bulk Power System Reliability Modeling Methods

Bulk power system reliability modeling techniques have evolved from traditional deterministic modeling methods to the current more advanced probabilistic modeling methods. Recently, some intelligent concepts, such as fuzzy set theory, have also been incorporated into probabilistic modeling techniques.

Deterministic Method

It is incumbent on power system planners and operators to ensure that customers receive adequate and secure energy supplies within reasonable economic constraints. Historically, such a task has involved the assessment of bulk power system reliability using deterministic criteria, which generally include a list of empirical contingencies involving the outages of some important power system components. With these contingencies in mind, planners and operators of the power system can incorporate sufficient redundancy so that any system failures during such contingencies can be prevented. The more comprehensive the list of contingencies, the lower the probability of a system failure resulting from contingencies not listed. Through such deterministic methods, a satisfactory degree of system reliability has been achieved in the past decades.

Probabilistic models

The reliability is regarded as the ability of a system to perform its required function under stated conditions during a given period of time. In the strict conception the reliability is a probability that the system is operating without failures in the time period *t*. Let us look at the main probabilistic characteristics of reliability. Reliability function *p*(*t*) is a function which expresses the probability that the system will operate without failure in the period *t:*

$$p(t) = p\{\hat{T} < t\}$$

where $\hat{T}$ period without failures, continuous random variable; *P* – symbol of probability. The function *p*(*t*) decreases if *t* increases, *p*(*t*) = 1 if *t* = 0. Non-reliability function or failure probability function *q*(*t*) is a function which expresses the probability that a failure will happen in the period *t*:

$$q(t) = 1 - p(t)$$

Distribution function of time without failure *F*(*t*) :

$$F(t) = p\{\hat{T} < t\} = q(t)$$

Density function of time without failures *f* (*t*):

$$f(t) = \frac{\partial F(t)}{\partial t} = \frac{\partial q(t)}{\partial t}$$

If intensity of failures is constant, the reliability function is the exponential function:

$$p(t) = e^{-\lambda t}$$

And

$$f(t) = \lambda e^{-\lambda t}$$

where λ – intensity of failures.

The exponential reliability function *p*(*t*) and distribution function *F*(*t*) of a power unit are shown in Fig.2. On the basis of density function we can evaluate the expectation, variance and standard deviation of the period without failures. Expected period without failure $\bar{t}$:

$$\bar{t} = \int_0^{\infty} t.f(t)dt$$

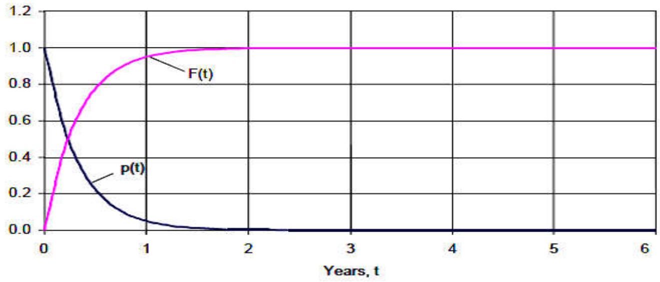

Fig 2 Reliability function *p(t)* and distribution function *F(t)* of power unit, λ = 3.

Variance of period without failures, which measures the dispersion of values away from the expected time to failure:

$$D_t = E(t - \bar{t})^2 = \int_0^{\infty} (t - \bar{t})^2 f(t)dt$$

Standard deviation of period without failures:

$$\sigma_t = \sqrt{D_t}$$

In practice the reliability evaluation takes place on the basis of expected failure rate and expected repair rate, or on the basis of mean time to failure and a mean time to repair. According to that the following probabilities are determined:

1. Unavailability (forced outage rate) of object *q*

$$q = FOR = 1 - p = \frac{\lambda}{\lambda + \mu} = \frac{r}{m + r}$$

2. Availability of object *p*

$$p = \frac{\mu}{\lambda + \mu} = \frac{m}{m + r}$$

where λ – expected failure rate; μ – expected repair rate; *m* – mean time to failure, *m* =1/ λ; *r* – mean time to repair, *r* =1/ μ . Here the probabilities *p* and *q* are the corresponding probabilities at some distant time in the future. Statistical indicators of reliability for power units are often changing within great limits and confidence limits of probabilities are ordinarily very large. This indicates the need to consider uncertain and fuzzy factors in the reliability modeling.

Uncertain probabilistic models

Uncertain probabilistic models are the probabilistic models, the parameters of which are given by crisp intervals and the values of parameters are uncertainties in those intervals. If the value of intensity λ is not given exactly, the intensity of failures must be described as an uncertain variable in the crisp interval. Then the reliability function is an uncertain probabilistic function:

$$p(t, \lambda_2(t)) \leq p(t) \leq p(t) \leq p(t, \lambda_3(t)$$

If λ_2 *and* λ_3 are constants, we have

$$e^{-\lambda_2 t} \leq p(t) \leq e^{-\lambda_3 t}$$

The exponential reliability function *p*(*t*) and distribution function *F*(*t*) of a power unit in the uncertain form are shown in Fig.3. The intensity of failures is given by intervals:

$$2 \leq \lambda \leq 3.5$$

The other characteristics and indicators of reliability in the uncertain probabilistic form can be analogically described.

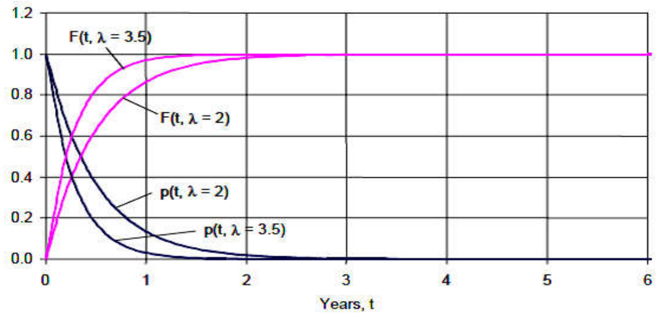

Fig 3 Reliability function $p(t)$ and distribution function $F(t)$ of a power unit in the uncertain form, $\lambda_2 = 3.5, \lambda_3 = 2$.

Fuzzy-Probabilistic Method

In recent years, some power system reliability probabilistic modeling methods have attempted to incorporate the fuzzy set concept in modeling system uncertainties. For example, fuzzy numbers are used to model uncertainties in system component failure and repair rates, fuzzy load duration curves are developed using a fuzzy number in each time step, and fuzzy power flow models are developed to identify possible system behaviors given specified uncertainties. These fuzzy representations of system uncertainties are then integrated into the probabilistic evaluation procedure. However, by using this fuzzy-probabilistic method, the computational burden increases significantly without a commensurate gain in the quality of results.

Fuzzy probabilistic models

Actually the limits of reliability characteristics are not given exactly. In reality the intervals of reliability characteristics values are fuzzy zones. Consequently we must use the fuzzy probabilistic models of reliability. The fuzzy probabilistic models are the probabilistic models whose parameters are given by fuzzy intervals. A fuzzy zone $\tilde{A}$ is defined in U as a set of ordered pairs:

$$\tilde{A} = \{(x, \mu_A(x) : x \in U\}$$

where $\mu_A(x)$ is called the membership function, which indicates the degree of that x belongs to $\tilde{A}$ The membership function takes values [0,1] and is defined so that $\mu_A(x) = 1$ if x is a member of $\tilde{A}$ and 0 otherwise. At that, if $0 < \mu_A(x) < 1$ the x may be the member of $\tilde{A}$. U is the given crisp set. The application of fuzzy systems in reliability analysis is nowadays expanding. A typical membership function of intensity λ is shown in Fig.4. Figure 5 shows the exponential reliability function *p(t)* and distribution function *F(t)* of a power unit in the fuzzy form if the membership function is $\mu(\lambda)$. The other indicators of reliability may be presented in the fuzzy probabilistic form in an analogical way.

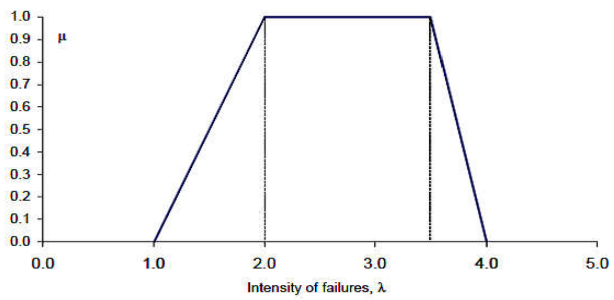

Fig 4 Membership function $\mu(\lambda)$

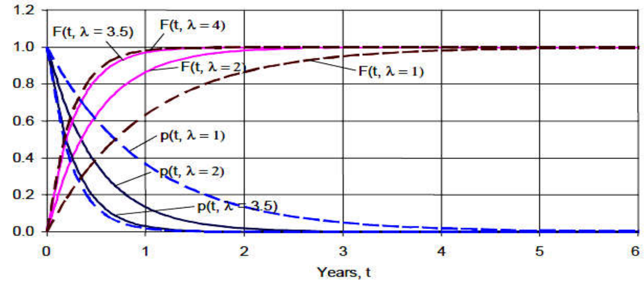

Fig 5 The reliability function $p(t)$ and distribution function $F(t)$ of a power unit in the fuzzy form

Reliability of power units

The models described above were used for reliability analysis of oil shale power plants in the Estonian power system in the years 2000–2005. Power units have two boilers per unit. Capacity of a unit with two boilers is 200 MW, and with one boiler 100 MW. The uncertainty intervals of reliability indicators for boilers, turbine and generator and for the whole unit are presented in Table 1. Table 1 shows that reliability indicators of the unit are changing within rather great intervals. Therefore the limits of intervals are inaccurate. The probabilistic models of reliability for power system generation in the uncertain probabilistic form are shown in Figures 6 and 7.

Table 1 Intervals of reliability indicators of oil shale power units 200 MW

(λ – expected failure rate; μ – expected repair rate, m – mean time to failure, $m = 1/\lambda$; r – mean time to repair, $r = 1/\mu$)

	Boiler	Turbine	Generator	Power unit
λ	1.38-4.45	1.0-1.3	0.12-0.23	7.31-10.45
μ	70-245	100-178	75-575	135-250
r	0.0043-0.0134	0.0049-0.0096	0.0014-0.0123	0.0023-0.0065
m	0.2136-0.4245	0.6-0.9	1.65-6.0	0.089-0.123
p	0.9392-0.9932	0.9762-0.9032	0.9956-0.9065	0.94032-0.9546
q	0.0056-0.0435	0.0056-0.0135	0.0005-0.0021	0.03213-0.0543

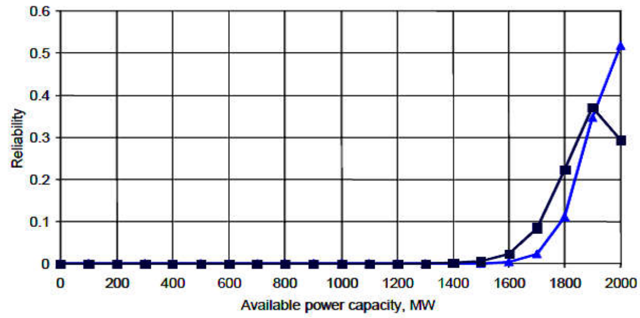

Fig 6 Uncertain probabilistic model of reliability for a ten-unit electric power system generation

If we consider the inexactness of confidence limits, it would be expedient to present the information about reliabilities and probabilities of failures in the fuzzy probabilistic form. The information about unit's reliability in the uncertain probabilistic and fuzzy probabilistic forms is presented in Table 2. The fuzzy probabilistic models of reliability for power system generation in the fuzzy probabilistic form are shown in Figures 8 and 9.

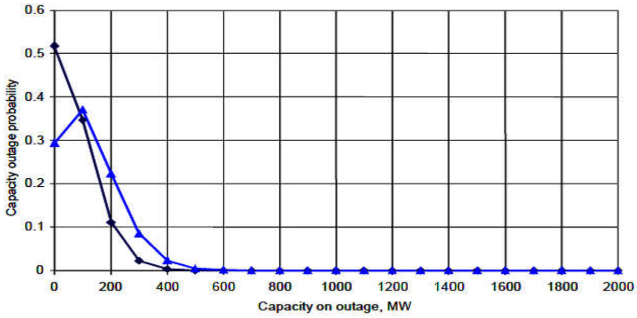

Fig 7 Zone of uncertainty for probability of capacity outage for a ten-unit power system

Table 2 Fuzzy intervals for reliability indicators

	Fuzzy essential points			
	$\mu = 0$	$\mu = 1$	$\mu = 1$	$\mu = 0$
λ	1.45	2.74	7.65	10.45
r	0.0034	0.0036	0.0069	0.0089
m	0.0890	0.1189	0.3100	0.6312
p	0.9301	0.9532	0.9715	0.9817
q	0.0060	0.0178	0.0234	0.0456

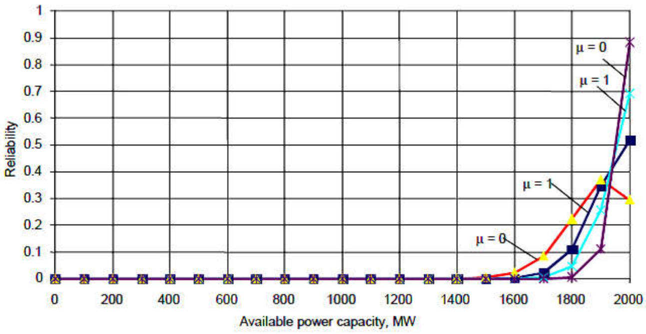

Fig 8 Fuzzy probabilistic model of reliability for a ten-unit electric power system generation

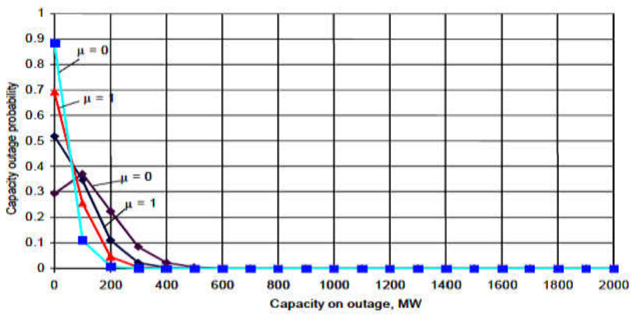

Fig 9 Fuzzy probabilistic functions of capacity outage for a ten-unit power system

The fuzzy probabilistic models enable to use exact probabilistic, uncertain probabilistic and fuzzy probabilistic information for describing the reliability characteristics and indicators of units.

Adequacy and Security Reliability Assessment

Bulk power systems must not only provide adequate generation and transmission capacity to meet the demand of customers while satisfying system operating constraints, but also be capable of maintaining system stability following faults, switching and other disturbances. Regarding these two aspects, the reliability of a bulk system can be evaluated by two attributes: adequacy and security. Adequacy refers to the ability of the system to supply the aggregate electric energy requirements of customers within component ratings and voltage limits when planned and unplanned component outages occur. Adequacy assessment involves system steady-state conditions of post-contingencies, i.e., the system is assumed to always reach a stable equilibrium point after equipment outages, and the dynamics of the transition from one state to another are neglected. The second attribute, system security, refers to the ability of the power system to withstand disturbances arising from faults or equipment outages. Security assessment involves system transient responses and cascading sequences after a disturbance. Transient responses include the fluctuations of both the system frequency and bus voltages. If the fluctuations exceed certain operating limits, cascading sequences, such as line and generator tripping, may occur and persist until the system completely separates or collapses.

Adequacy Assessment

The major difficulty in adequacy assessment involves the enormous computational effort required to analyze as many contingencies that may have a nonzero contribution to system unreliability as possible. The massive computational demand is a result of the following two factors: The first involves the large system size and the resulting large number of system states that must be assessed. It is usually not feasible or even possible to investigate all the contingencies of a power network. In practice, only credible outage states up to a certain contingency level are investigated. Research attempting to solve the above two problems are further classified as adequacy and security-constrained adequacy evaluations, which are reviewed separately.

Generating Capacity Adequacy Evaluation

Hierarchical level I (HL-I) corresponds to analysis of the generation function only. This was the earliest power system reliability problem addressed, with the first work during the year 1933-1934, with a later seminal contribution in 1947. The so-called "Calabrese" method forms the basis of the loss of load approach which is still the most widely used probabilistic technique in the reliability evaluation of generating capacity. In HL-I evaluation, the reliability of the transmission is ignored, and the only concern is in estimating the necessary generating capacity to satisfy the system demand and to perform corrective and preventive maintenance on the generating units. Adequacy evaluation at HL-I involves determination of the total system generation required to satisfy the total load requirement. In the study of adequacy evaluation, the reliability of the transmission a distribution zones and their ability to move the generated energy to the customer load points are not included. The basic model at HL-I is shown in Figure 10.

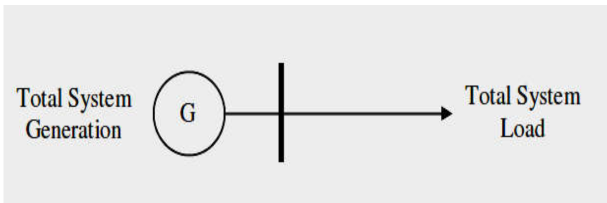

Fig 10 Basic Model

The basic modeling approach for the generating system adequacy assessment consists of three parts as shown in Figure 11. The generation and load models are convolved to form an appropriate risk model where the element of interest is the risk of generation capacity less than the load. In short, adequacy evaluation of generation systems consists of three general steps:

1. Create a generation capacity model based on the operating characteristics of the generating units
2. Build an appropriate load model
3. Combine the generation capacity model with load model to obtain a risk model

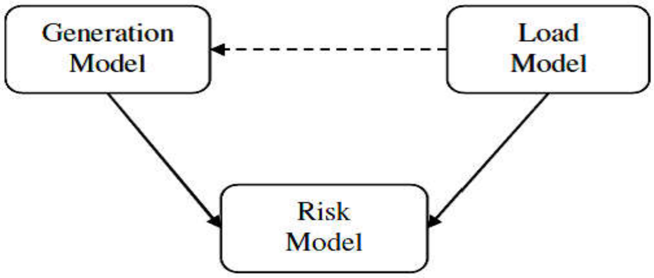

Fig 11 Conceptual Model in Adequacy Assessment at HL-I

The risk indices obtained are overall system adequacy indices and do not include transmission constraints and transmission reliabilities. The most widely used analytical technique in HL-I evaluation is the loss of load approach. This process has been extended to include the loss of energy. Both analytical and simulation methods have their own merits and demerits. Analytical techniques can provide the expected index values in a relative short computation time. The reliability indices obtained indicate the ability of the generating facilities to meet the system demand. In the analytical method, the generating system model used for generation capacity adequacy assessment is a Capacity Outage Probability Table (COPT) which can be created using a recursive technique and for the load model, the daily peak load or hourly load for a period of one year is normally used to form the Load Probability Table (LPT). According to Wang and McDonald (1994) the process of evaluation of power system reliability starts by creating a mathematical model of a system or a subsystem and then proceeding with a numerical solution, summarized in the following general steps:

1. Define the boundary of the system and list all the components included
2. Provide reliability data such as failure rate, repair rate, repair time, scheduled maintenance time, etc., for every component
3. Establish reliability model for every component
4. Define the mode of system failure, or define the criterion for normal and faulty systems
5. Establish a mathematical model for the system reliability and its basic assumptions
6. Select an algorithm to calculate the system reliability indices

Generating system reliability evaluation is an important aspect for future system capacity expansion. It provides a measure of reliability or adequacy to make sure that the total generation system capacity is sufficient to provide adequate electricity when it is needed. The estimation of reliability indices is essential at the time of planning and expansion. Generally various number of basic reliability indices such as Loss of Load Probability (LOLP), Loss of Load Expectation (LOLE), Loss of Energy Probability (LOEP), and Loss of Energy Expectation (LOEE) are used to assess generating capacity adequacy. The power system reliability analysis needs huge volume of failure data, which are heterogeneous in nature. A convenient data representation model is required to enhance the interoperability between heterogeneous applications.

Current Trends in Power System Reliability Estimation

The physical structure of the power system network changes dynamically in the deregulation environment and its size is keeping on increasing to meet the power demand. Consequently, the power system operations are becoming extremely complex. As the electricity industry moves towards restructuring, it seems clear that system reliability will continue to be an extremely important area of research. Ramachandran and Sankaranarayanan (1993) have developed a recursive algorithm to extract minimal-cuts from fault tree representation of the power system networks and hence obtained the system failure probability. A non-linear tree structure is used to construct fault trees that represent system conditions symbolically and include all the basic fault events that may occur or expected to occur in the system. This approach was tested with a power system of 3 buses and 5 lines, a power supply system and with a sample transmission system. Ozdemir (2010) demonstrated the reliability estimation of a sample transmission network shown in Figure 12 using minimal-cuts.

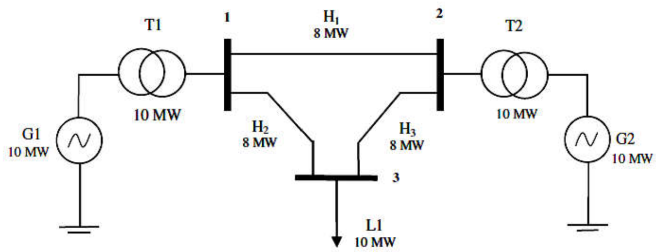

Fig 12 Sample Power Transmission System

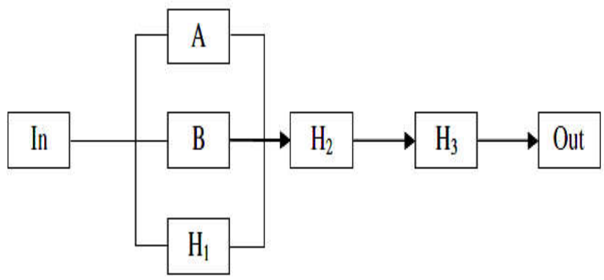

Fig 13 Series-Parallel Representation of Sample Power Transmission Network

The power transmission capacities of the three transmission lines H1, H2 and H3 are 8 MW where a 10 MW load is consumed by two generators G1 and G2. The reliability values of the components are given as follows.

RG1 = 0.98, RT1 = 0.99
RG2 = 0.97, RT2 = 0.98
RH1=RH2= RH3 = 0.98
The equivalents of G1-T1 and G2-T2 are represented by A and B respectively.
RA = RG1
RT1 = 0.9702
RB = RG2

RT2 = 0.9506
QA = 1 - RA = 0.0298
QB = 1 - RB = 0.0494

where, QA and QB are the failure probabilities. Since a minimal path should provide a power of 10 MW, the components A, B and H1 comprise 2/3 of the system which is in series with H2 and H3 as shown in Figure 13.
The extracted minimal paths are,{ A H1 H2 H3, B H1 H2 H3 and A B H2 H3 }and the derived minimal-cuts are,{ H2, H3, A B, A H1 and B H1 }
Using these minimal-cuts, the failure probability of the system is estimated as follows:

$$Q_S = Q\left[\bigcup_{i=1}^{5} C_i\right]$$

$$Q_S = \sum Q(C_i) - \sum Q(C_i \cap C_j)$$

(by omitting the third and higher order terms)

$$Qs \cong Q_H + Q_H + Q_A Q_B + Q_A Q_H + Q_B Q_H - Q^2_H$$

$$Q_S \cong 0.043056$$

and hence the reliability of the sample transmission network Rs is estimated as follows:
RS = 1- QS = 0.956944

The above power transmission network has been represented as a fault tree with all possible fault events and minimal cuts are extracted using the recursive algorithm proposed by the authors, Ramachandran and Sankaranarayanan (1993). The probability of occurrence of the fault event represented as the root element of the fault tree is estimated. A logical database is created to access the intermediate event by pre-order traversal and by using the exact location of the event in the fault tree, the probability of occurrence of this event is estimated by using Boolean operations AND / OR, which are associated to constitute that fault event.

Security-Constrained Adequacy Evaluation (SCAE)

This strategy is referred to as security-constrained adequacy evaluation SCAE). System security constraints include bus voltage limits, line flow limits, real power and reactive power generation limits, and so on. In practice, when generator or line outages occur or line overloads resulting from outages occur generating units should be rescheduled so that the power system can maintain generation-demand balance and alleviate line overloads. If violations corresponding to the bus voltage limits exist, reactive power (generation, transformer taps, and shunt compensation) must be rescheduled to eliminate abnormal voltages in the system. The purpose of these remedial actions is to keep the system operating normally, and thus avoid load curtailment, if possible, or to minimize total load curtailment, if unavoidable. Since the optimal power flow technique is an important issue related to the effects analysis procedure in SCAE, a brief review of the formulation and the solution of optimal power flow is provided in the following section.

Optimal Power Flow

Optimal power flow (OPF) is a mathematical optimization tool for adjusting the power flow in a power network to achieve the optimal value of a predefined objective while satisfying system operating constraints. OPF has undergone intensive research and development over the past several decades. Mathematically, the general OPF problem can be expressed as follows.

Minimize $f(x, u)$ Subject to $g(x, u) = 0$, $h(x, u) \leq 0$

$u^{\min} \leq u \leq u^{\max}$,

where $f(x, u)$ objective function , $g(x, u) = 0$ power flow equations $h(x, u) \leq 0$ operating constraints x vector of system state variables u vector of control variables. $u^{\min} \leq u \leq u^{\max}$ feasible region of control variables

The OPF objective function varies with different operational objectives. Typical examples of objective functions are minimum generation cost minimum system transmission loss, voltage and reactive power optimization, preventive and corrective control optimization, and so on. In reliability assessment, the objective may include the minimum amount of remedial actions, minimum load curtailments, and so on. A predefined objective can be achieved if control variables in the system are available for adjustment. Control variables usually include MW/MVAR generation adjustment; shunt capacitor/reactor switching, phase shifter adjustment, transformer tap adjustment, load transfer, area interchange, and load shedding. Constraints in the OPF generally contain equality and inequality equations. Equality constraints are usually power flow equations. Inequality constraints consist of functional operating constraints, including branch flow limits, bus voltage magnitude limits, and so on. In addition, the feasible region of control variables is contained in the constraints set, including unit active and reactive power output limits, transformer tap limits, and so on. Some variations in formulating the OPF problem exist with its application in different areas. These variations mainly include the decomposition of real and reactive OPF, contingency constrained OPF, stability constrained OPF, and so on. Also, a wide variety of optimization techniques, such as linear programming (LP), quadratic programming, nonlinear programming, hybrid versions of linear programming, and integer programming, have been employed to solve the formulated OPF problems. Because of the large-scale nature of the problem and the resulting computational complexity of reliability assessment, the linear programming (LP) technique, which has a relatively simple formulation and is capable of providing fast solutions, is the most attractive tool.

Integrated Adequacy and Security Assessment

The security assessment of a composite power system involves evaluating system behavior while integrating transient stability as well as cascading sequences after a disturbance. For the correct assessment of system security, the contingency analysis has to be repeated for all significant initial conditions and at different points in time to account for the impact of time-dependent factors, including the transient behavior of generators, the operation of many types of protection schemes, the automatic actions of different controls, and operators' actions. Nowadays, a major effort in the security assessment has been devoted to extending existing adequacy assessment techniques to include the assessment of system security. Other work is based on time domain simulation that achieves the security assessment.

Integration of Transient Stability Limit

A framework that evaluates both the adequacy and security reliability of the system is presented in. In security analysis, the system transient stability limit is identified by comparing the fault clearing time with the critical clearing time. Providing critical clearing time requires a transient stability evaluation. For unstable states, remedial actions are applied, and some indices corresponding to the security evaluation are also provided. The security assessment presented in reference also takes into account the cascading sequences besides the transient stability. System states are classified into nine types: adequate, inadequate, partially adequate, stable, unstable, secure, not secure, marginally adequate, and system collapse states. Based on the classified states, a possible sequence of events after the occurrence of a disturbance is built. Integration of Security Constraints the security assessment technique presented in is based on the previously described security-constrained adequacy evaluation. In, besides the basic operating constraints that have to be satisfied for the steady- state performance, a transient-performance constraint set that can reflect the transient behavior of a power system when subject to system faults is formed. In, instead of introducing new constraint sets, dynamic system models are suggested for use in determining system operating limits that include security consideration.

Web Service Based Power System Reliability Data Generation Model

Internet provides a heterogeneous environment for Web applications development. Number of power system applications, which are hosted in the Web is countless and it is a growing phenomenon. Many power utilities on the Web provide the various applications that include power system planning, on-line operations monitoring, state estimation, stability analysis, smart metering, energy management, data acquisition and information sharing. These applications have been developed in different platforms using different programming and scripting paradigms. The data needed for those applications are in different formats and are scattered desperately. Interoperability becomes a major issue in most of the Web enabled power system applications. Most of the power system applications store their planning, operational and maintenance data in relational databases. The major problem with most of the relational databases is their incompatible formats while accessing by various power system applications of heterogeneous nature. In order to enhance the interoperability and for flexible data sharing between power system applications in a distributed environment, it becomes very essential to convert the power system data stored in the relational databases into XML documents. An efficient, reliable and secure method is required for transforming the data and for transferring the same in a distributed environment, especially when the size of data is large as in case of real time large power systems. Since in the deregulated environment, the various power utilities are interconnecting their individual power systems in order to meet the demand and to meet the quality requirements, there is a real problem of communication for exchanging the data among various applications.

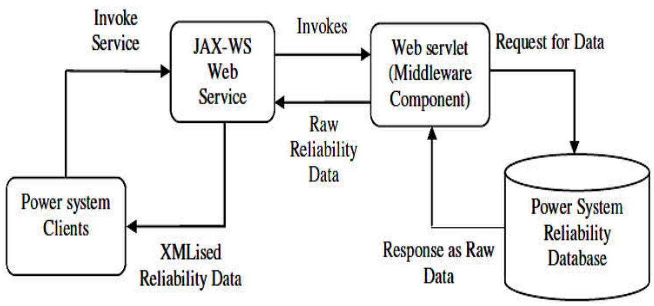

Figure 14 XM Lised Power System Reliability Data Generation Model

The conversion of power system data into text based XML document is preferred in SOAP messages, both in request and response payloads. The proposed Web Service model shown in Figure 14 has the capability to dynamically generate the power system reliability data in XML, fetching the required data from the database. The proposed XMLised power system data representation model significantly reduces the engineering efforts required to integrate its data in the Web services environment. This ensures interoperability between various power system applications in a heterogeneous environment. The major steps involved in the Web service based power system reliability data generation model in JAX-WS environment are data representation, defining endpoint interface, its implementation, service description, service deploying in virtual server, creation of client side and server side artifacts and invoking. The proposed model is tested with the Roy Billinton Test System (RBTS) with 6 Buses whose single line diagram is shown in Figure 15.

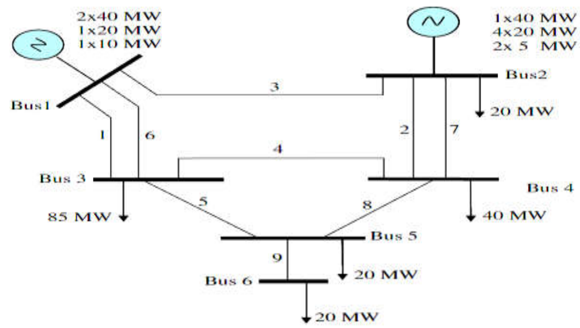

Figure 15 Single Line Diagram of the RBTS

CONCLUSION

The concepts of power system reliability and the current trends in reliability analysis especially of generation and distributed systems are reviewed in this chapter. An innovative and comprehensive solution is obtained using XML annotations, which represents the power system reliability data in XML form that confines to XML standards and specifications. An annotated Web service model for the representation of power system data in XML format has been implemented using JAX-WS environment to enhance the interoperability between power system clients and reliability estimation service providers. The XML data generation model has been tested with IEEE-RTS and RBTS systems.

1. The use of uncertain probabilistic and fuzzy probabilistic models is a suitable method for the analysis and control of power system reliability, since

they are more general and more complete than traditional probabilistic models of reliability.

2. Power generation at wind power plants is a random process. Two dimensioned distribution functions of power values and power durations can be used for modeling and making prognosis of wind power generation.
3. Uncertain and fuzzy models have also a prospect for modeling wind power generation.

A comprehensive approach for bulk power system reliability assessment, i.e., the security-constrained adequacy evaluation (SCAE) methodology, is developed to evaluate the ability of the system in supplying the electric load while satisfying security constraints. Research contributions have been made in following areas:

1. The single phase quadratized power flow (SPQPF) model is applied in the proposed SCAE methodology for bulk power system reliability assessment. Compared with the traditional power flow model, the SPQPF model yields improved contingency selection and ranking accuracy, speeds up the procedure of the effects analysis because of its faster convergence characteristics, and makes the effects analysis more realistic with its ability to model complex load characteristics.
2. An improved critical contingency selection scheme is developed to efficiently identify and rank critical contingencies with high accuracy. Specifically, the system state linearization approach is investigated to reduce the error introduced by the linear approximation in the traditional performance index linearization methods for contingency selection and ranking. The system state linearization approach includes higher-order terms in the performance index calculation procedure to trace nonlinear variations of the performance index for a post-contingency situation and therefore effectively reduce misranking in the contingency selection and ranking procedures.
3. A non-divergent optimal quadratized power flow (NDOQPF) algorithm that performs contingency effects analysis is proposed. Quadratized remedial action models are developed, and the concept of the remedial action control variable is used to represent the availability and amount of system remedial actions. Compared with the traditional power flow solution procedure, the NDOQPF algorithm has the following merits:

- It is able to simulate contingencies in a realistic manner to capture the system response including major controls and adjustments. In addition, because of its efficiency, the overall computational effort of SCAE is reasonable;
- If a solution exists; it guarantees convergence; if a solution does not exist, such as when multi-level contingencies are considered and the system is severely stressed, it can provide a sub-optimal solution that may include load shedding for the system.
- It is applicable to both a regulated and deregulated power system environment. In particular, in a deregulated environment in which the system is more likely to be heavily stressed and may be operated in different power flow patterns from the ones it was originally designed to operate in, the NDOQPF is capable of efficiently solving the ISO/RTO operational model and providing solutions under all conditions.
- The impact of protection system hidden failures on bulk power system reliability assessment is investigated. A circuit breaker-oriented substation model is introduced to include the detailed substation configuration as well as the protection system scheme in the system network model. In addition, the impact of advanced system real time monitoring technologies on detecting protection system hidden failures is analyzed. Also, a hidden failure effects analysis method is developed to obtain hidden failure outages following any possible initial equipment outages. The security-constrained adequacy evaluation methodology is extended to evaluate contingencies resulting from protection system hidden failures as well as other contingencies resulting from independent and common-mode outages so that the impact of protection system hidden failures on bulk power system reliability assessment is included.

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