Early History on the Application of Probability Methods in the Evaluation of Generating Capacity Requirements

Roy Billinton University of Saskatchewan

Kelvin Chu General Electric Energy Consulting Group

This presentation is focused on the early history of the application of probability methods in the evaluation of generating capacity reserves and requirements, with particular attention to the development and evolution of the Loss of Load Probability (LOLP) index of one day in ten years.

The material is presented in three segments.

“Bibliography on Application of Probability Methods In the Evaluation of Generating Capacity Requirements”
R. Billinton, Paper No. 31 CP 66-62, IEEE Winter Power Meeting, New York, January 30-February 4, 1966.

Tracking the Origin of the One Day in Ten Years LOLP Criterion

Response to the article in the July/ August, 2015 IEEE Power & Energy Magazine

The following comments were used to present the "Bibliography" at the IEEE Winter Power Meeting in 1966 in New York

In general, it can be said that interest in the application of probability methods to the evaluation of capacity requirements became evident about 1933. Relatively little published material is available, however, for the period 1933 to 1947, when the first large group of papers appeared and are shown as [11] to [17] in the Bibliography.

American Institute of Electrical Engineering Conference, Chicago, 1947

Session on the application of probability theory to the determination of generating capacity reserve.

11. “Generating Reserve Capacity Determined by the Probability Method”, G. Calabrese, AIEE Trans. 1947, Vol. 66, pp 1439-50.

12. “Calculating Probability of Generating Capacity Outages”, W. J. Lyman, AIEE Trans. 1947, Vol. 66, pp 1471-77.

13. “Outage Expectancy as a Basis for Generator Reserve” H. P. Seelye, AIEE Trans. 1947, Vol. 66, pp 1483-88.

14. “Probability Methods Applied to Generating Capacity Problems of a Combined Hydro and Steam System”, E. S. Loane, C. W. Watchhorn, AIEE Trans. 1947, Vol. 66, pp 1645-67.

This group of papers by Calebrese, Lyman, Seelye, Loane and Watchorn presented the basic concepts upon which some of the methods in use at the present time are based. The 1947 group of papers proposed various methods of applying probability theory to this problem. These methods with some modifications are those now generally known as the:

"Loss of Load Probability Approach",
"Loss of Energy Probability Approach",
"Frequency and Duration of Outage Approach".

They are described in the 1960 AIEE Committee Report on the "Application of Probability Methods to Generating Capacity Problems" [72].

The AIEE Subcommittee on the "Application of Probability Methods" (APM) chaired by G. Calabrese was created in 1948.

This Subcommittee produced the AIEE Committee Report on "Outage Rates of Steam Turbines and Boilers and of Hydro Units" [20], in 1949. The data in this report were collected by committees of the Edison Electric Institute. This report also contained important comprehensive definitions of equipment outage classifications. Later reports on this subject by this Subcommittee appeared in 1954 [30] and 1957 [36].

The three AIEE Subcommittee Reports on generating unit forced outage experience published in 1949, 1954 and 1957 had generally been restricted to thermal unit information (with the exception of a short section on hydraulic equipment in the 1949 report). An important paper by Brown, Dean and Caprez [74] was published in 1960. This paper presented the results of a statistical study of five years of data on 387 hydro-electric generating units. This investigation utilized punched cards for the initial collection and sequential processing of the data.

In 1961, the AIEE APM Subcommittee produced the "Manual For Reporting The Performance Of Generating Equipment" [79]. This manual outlined a comprehensive procedure for recording the outage data and a means of analyzing the recorded data using digital equipment.

Up to about 1954, the bulk of probability studies had been done either by hand or with conventional desk calculators, as illustrated by [28]. "Tables of Binomial Probability Distribution to Six Decimal Places" AIEE Committee Report, AIEE Trans. Vol. 71, Aug. 1952, pp, 597-620.

In a general paper in 1954 (Reference #31 in the Bibliography) Watchorn and his discussers noted the possible benefits of using digital computers to reduce the tedious arithmetic required in these studies. Their utilization was demonstrated in a 1955 publication [32] by Kirchmayer et al. This paper illustrated the use of digital equipment in system expansion studies to determine the economic size of generating unit additions.

Several excellent papers appeared each year until in 1958 a second large group was presented and published. This group of papers modified and extended the methods proposed by the 1947 group and also introduced a somewhat more sophisticated approach to the problem by the way of "Game-Theory" or "Simulation" methods. The application of these techniques were proposed and illustrated in a series of joint papers by the Public Service Electric and Gas Company and the Westinghouse Electric Corporation. [56 to 70 excluding 58]. Additional papers in this area appeared in 1961[80] and 1962 [81] but since that time, interest in this approach may have declined. A recent Federal Power Commission Report stated that former users of the Monte Carlo approach "are currently substituting the loss of load probability type computations for the gaming approach".

Up to 1963, almost all the papers on this subject were confined to what might be called the "static generating requirement" with only brief mention of the problem of "spinning reserves". (An exception to this is [31], by Watchorn).

An important paper [88], based entirely on the application of probability methods to system spinning reserves, entitled "Application of Probability Methods to the Determination of Spinning Reserve Requirements for the Pennsylvania-New Jersey-Maryland Interconnection" was published in 1963.

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A 1963 paper by Watchorn [86] discussed characteristics of load growth as related to the addition of generating capacity facilities. A further paper by Watchorn in 1964 [94] reviewed the basic characteristics of probability methods in this area and provides a basic understanding of the applicability of these techniques.

A glance at the Author Index concluding the Bibliography immediately indicates those authors who have made a substantial contribution to this area. Of these many noteworthy contributors, it is interesting to note that Watchorn, whose publications in this area span a time period of some twenty years, provided one of the earliest and one of the latest papers.

Tracking the Origin of the One Day in Ten Years LOLP Criterion

The first coordinated attempt to discuss the application of probability techniques in generating capacity reserve assessment is considered to have occurred at an American Institute of Electrical Engineering Conference in Chicago in 1947 where four papers [11-14] were presented on this subject. All four papers proposed the application of probability theory to consider generating unit outages and presented some examples of a Loss of Load (LOL) index but did not suggest a criterion for an acceptable level of reliability.

Reference 11, [1947] by G. Calabrese presented the basic methodology and illustrated the Loss of Load Probability (LOLP) using daily values of 0.00001, 0.0001 and 0.001 but did not specifically indicate a criterion value.

Reference 12, [1947]by W.J. Lyman proposed the use of MW outages and did not consider the LOLP.

Reference 13, [1947] by H.P. Seelye suggested that a reasonable interval between the occurrence of generating capacity deficiencies might be once in 20 years, 30 years or 50 years but did not mention a LOLP value.

Reference 14 [1947] by E.S. Loane and C. W. Watchorn noted an acceptable lower LOLP limit of 1 day in 27 years and an upper limit of 1 day in 88 years and implied that 1 day in 8.66 years would perhaps be undesirable.

It is important to note that all the authors suggested that the choice of an appropriate level of service reliability for a system should be based on personal judgement and local conditions.

The four papers [11-14] presented at the 1947 meeting in Chicago can be considered as the starting point in the evolution and application of probabilistic techniques in generating capacity reliability assessment.

These papers also initiated the determination of the generally accepted Loss of Load Expectation index criterion of 0.1 days/year presently in use.

In order to track the origin of this criterion, the papers listed in the "Bibliography" that were deemed to be related to generating capacity planning or reserve requirements were reviewed. This review focused on the following requirements.

Did the paper mention the application of LOLP, and if yes, was a criterion provided.

If a criterion was provided or a value quoted, was there a justification given for the criterion or value.

The following is a list of the papers that indicated the use of LOLP and any suggested criterion or value. References 11-14 were covered earlier.

Reference 17, [1948] by G. Calabrese discussed LOLP but did not indicate any specific value.

Reference 22, [1950] by C.W. Watchorn utilized the LOLP approach and suggested a criterion of 1 day in 8 to 10 years and used 1 day in 8.66 years as an example in his calculation.

He also stated that: "It is believed that a reasonable level of service reliability, when the effect of probable load forecasting error is included in the evaluation, is the probability of failure to carry the load in the order of an average rate of one day in 8 to 10 years".

Reference 23, [1950] by G. Calabrese suggested that a LOLP of 1 day in 50 years after voltage reduction should be satisfactory. He also indicated that the reliability level may be different for different generation mixes and should include all local factors.

In the discussion to this paper, C.W. Watchorn noted that:
"The level of service reliability of a loss of load expectation of in the order of the average rate of one day in ten years is both reasonable and adequate. The discusser has already so recommended or indicated on several occasions".

He quoted three of his papers [14, 22 and 25] in this statement as if the issue had been fully discussed in these papers. In fact, he did recommend or indicate the criterion in these papers but didn't provide any information on how or why this value was chosen.

Reference 24, [1950] by M.J. Steinberg used a criterion of 1 day in 7 years as an example but provided no justification.

Reference 25, [1951] by C.W. Watchorn states in this interesting and detailed paper.
"It is believed that a reasonable and adequate degree of reliability is provided with an objective risk of failure to carry the load at an average rate of one day in 10 years or 0.1 days/year provided the effect of all the factors affecting capacity requirements are evaluated as shown herein".

Note: this is expressed as a belief statement without additional justification.

Reference 27, [1951] by H.T. Stranrud used a LOLP of 1 day in 14.6 years in his example and indicated that the reliability level should be decided for each system by considering such factors as the cost of reserves and the possible consequences of dropping load.

Reference 34, [1956] by M.J. Steinberg and V.M. Cook uses a 1 day in 7 years criterion for the examples shown in the paper. It was stated as being based on judgement and that it generally conforms with the views of other companies employing this method.

Reference 37, [1957] by L.K. Kirchmayer et al states that:
“The expansion plans in the paper were developed assuming that the standard of reliability of the system was such that sufficient generating and interconnecting transmission must be available so that the probability of loss of load approximates one day in 10 years”.

The paper also states that the average reliability standard was not universally applicable and there is a need for a better standard to balance between the economic loss of failure and the cost of providing service. In the discussion to this paper, C.W. Watchorn suggested that a criterion of 1 day in 10 years approximated fairly closely the results of such an economic standard of service reliability. No justification was provided.

Reference 42, [1958] by A.P. Jones and A.C. Mierow utilizes a LOLP of 0.000555 which equates to one day in 7 years considering 257 peak load days/yr.

Reference 43, [1958] by H. Halperin and H.A. Adler introduces a frequency and duration approach to generating reserve assessment using an index of 1/5 years without voltage reduction. "Like other similar proposal criteria of service reliability this upper limit of once in 5 years is based essentially on judgement". This is a frequency index not an expected duration index. This pioneering paper stimulated some excellent discussion.

Reference 40, [1958] by H.D. Limmer utilized a 1 day in 10 years LOLP based on 253 weekdays.

Virtually all the applicable references from this point on used a LOLP index of 1 day in 10 years in their applications.

Reference 72 [1960] is an important reference developed by a Working Group of the AIEE APM SubCommittee. The paper presents the results of three separate reliability measures applied to the same problem. The three methods are designated as:

1. **Loss of load probability,**
2. **Loss of energy probability and**
3. **Interval between outages.**

This is a benchmark paper which created some excellent written discussion. No specific LOLP criterion is given.

The paper states that:
"The selection of a satisfactory level of reliability or a corresponding index appropriate to any methods of measurement requires at some point the exercise of informed judgement".

The paper also states in regard to the loss of load probability approach that:
"Regardless of the form in which the result is presented, its significance as a probability of existence of a specified condition, and nothing more, must be recognized".

In his discussion of the AIEE WG paper, C.W. Watchorn suggests that 0.1 day of failure per year or 1 day of failure in 10 years is a generally accepted standard of service reliability.

The creation and movement towards the use of a LOLP of one day in 10 years or a LOLE of 0.1 days/year as a generally accepted generating capacity adequacy criterion can be briefly described as follows.

In Phase 1 from 1947 – 1950, no specific LOLP was suggested and authors generally investigated a range of LOLP values. Most authors also agreed that the objectives for service reliability would be different for different systems and that they had to be determined with judgement and based on local conditions.

In Phase 2 from 1950 – 1960, the LOLP values presented in various papers began to converge to a narrower range, i.e. from one day in 5 years to one day in 15 years. By 1960, the LOLP index was in the range of one in 5 years to one in 10 years.

In Phase 3 from 1960 on, the LOLP index of one day in 10 years seems to have been widely recognized by both academics and industry and most papers used or quoted this value as a standard.

Based on the review of the papers listed in the "Bibliography", it appears that C.W. Watchorn was the person who first proposed a LOLP of one day in ten years as a reasonable criterion for reserve capacity planning. It is interesting to see how his thinking evolved over time as expressed in his publications..

In 1947, he commented that one day in 27 years and one day in 88 years respectively were acceptable lower and upper limits with one day in 8.6 years being in the unacceptable range [14].

By 1950, he suggested one day in 8 to 10 years and used one day in 8.6 years in an example calculation. He did not provide any justification and wrote in [22]:

"It is believed that a reasonable level of service reliability, when the effect of probable load forecasting errors is included in the evaluation, is the probability of failure to carry the load of in the order of an average rate of one day in from eight to ten years".

By 1957 he seemed to consider a LOLE of 0.1 days/year as a criterion that corresponded to an economic standard of service reliability. His discussion on the 1960 AIEE Working Group report [72] suggests that the use of 0.1 days/year is now a tradition but "the tremendous advantage of money saving might warrant a break from this tradition". By 1964, he appears to quote the use of a LOLE of 0.1 days/year without any qualification.

Many reports have been published since 1960 that indicate the use of a LOLP index of one day in 10 years in generating capacity adequacy assessment.

Closing Comment

It should be noted that the numerical value of the LOLP produced in a particular generation adequacy study is highly dependent on the factors incorporated in the analysis. As an example, consider two studies of a given system. In the first study, no load forecast uncertainty is considered. In the second study, significant load forecast uncertainty is included. The calculated LOLP in the second case will be higher than that in the first case, and the system load carrying capability at the criterion risk will be lower than in the first case. There are a number of important factors that create similar effects. The use of a particular LOLP criterion such as one day in 10 years as the system criterion should include recognition of the standard factors that are included in the analysis.

Comments on the Early Evolution of LOLP History Article

"In the 'History' article, it is pointed out that an LOLP of one day in ten years (or an LOLE of 0.1 days/year) was gravitated to fairly early-on, and has persisted to this day. Scant attention has been given to explicitly factoring-in what the cost or benefit to power users (and society in general) might be if some other criterion and/or value was chosen to help determine how much installed load-serving capacity (both supply and demand-side) is optimal."

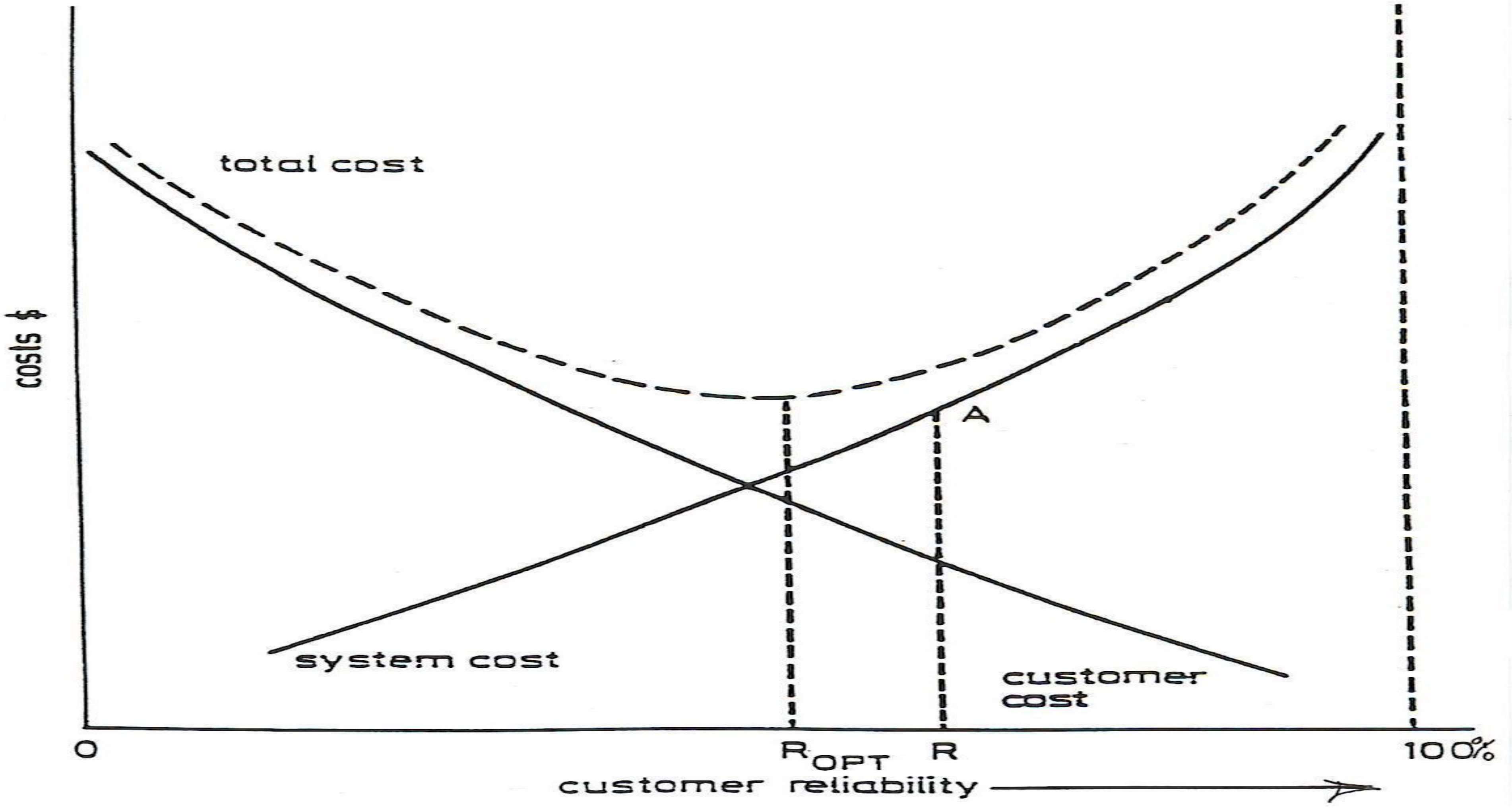
Comments on the Early Evolution of LOLP History Article

"In the last five decades the importance of having reliable electric power has increased, as has the cost of outages. Simultaneously, the technical and regulatory terrain has also changed significantly. Yet, the same reliability objective function target has endured as if the world had remained static. Thus, in my own personal opinion, the time has long been ripe for engineers and policymakers to start with a clean sheet and determine what the proper LOLP/LOLE figure-of-merit (and/or perhaps some other index) should be today."

Response to the Comments

Considerable work has been done on generating capacity reliability assessment since the early 1960s when the LOLP criterion of 0.1 days/year was established. This includes work on considering the "cost or benefit to power users" associated with different levels of generating system reliability and the determination of optimal capacity reserve margins. This is a specific application of the more general concepts of reliability worth/cost analysis to generating capacity adequacy assessment. Value based reliability assessment (VBRA), can and has been, applied to generation, transmission and distribution systems.

Reliability Cost/Worth



A key factor in VBRA is the cost associated with system failure and the residual uncertainties associated with assessing this cost. In regard to electric power systems, supply failures result in customer interruption costs, which vary considerably for different customers, customer sectors and their location in the system.

The paper "Comprehensive Bibliography on Electric Service Interruption Costs", R. Billinton, G. Wacker, E. Wojczyski, IEEE Trans. PAS, Vol. PAS-102, No. 6, June 1983 contains a wide array of publications relating to the theory and results of research into reliability worth. It is largely focused on the numerical evaluation of reliability worth associated with electric power supply.

A further publication entitled "Comprehensive Bibliography on Reliability Worth and Electric Service Consumer Interruption Costs: 1980-1990", G. Tollefson, R. Billinton, G. Wacker, IEEE Trans. PS, Vol. 6, No. 4, November 1991, pp. 1508-1514 extended the list of available material in this area.

This paper includes information on the series of customer sector outage cost studies conducted by the Power System Research Group at the University of Saskatchewan in which approximately 50,000 questionnaires were sent out over a 12 year period to electric power consumers across Canada.

The two bibliographies noted contain information on a wide range of research, governmental and utility organizations engaged in collecting customer outage cost data and conducting VBRA analyses.

International interest in this area is documented in a CIGRE Report entitled "Methods to Consider Customer Interruption Cost in Power System Analysis" compiled by CIGRE Task Force 38.06.01 with representation from fourteen countries.

Data obtained from a series of customer sector surveys were subsequently used in a VBRA study of Ontario Hydro's generating capacity adequacy criterion and the optimum capacity reserve margin. This activity was called the System Expansion Program Reassessment (SEPR) Study and examined generation system reliability and other issues. The SEPR Study included analyses of generation expansion programs with capacity reserves varying from 18 to 38%. The total system cost profile which includes expected customer outage costs shows relatively little change in the minimum total cost over a range of reliability levels.

The judgement was made that it is preferable to be on the higher reliability end of the minimum portion of the curve rather than on the lower end. The decision was driven by the idea of recognizing unquantified risk not covered by the analytical model and the fact that total customer costs increase more rapidly at lower reliability levels than at higher levels. The costs associated with having a little too much reserve is considerably smaller than not having enough reserve. It was also recognized that estimating customer interruption costs is an imprecise process involving a large amount of experience and judgement.

The basic conclusions regarding the nature of the total system costs profile as a function of the reserve capacity margin are supported by a study conducted by the Electric Power Research Institute (EPRI) entitled "Costs and Benefits of Over/Under Capacity in Electric Power System Planning ". (EPRI EA-927, Project 1107 Final Report, October 1978). The report shows results for four participating utilities (LILCO, TVA, PG&E, WEPCO). In each case, "the region of lowest cost" is a major portion of the total system cost profile making it difficult to easily select a suitable point.

The Working Group of the AIEE Subcommittee on the Application of Probability Methods stated in their 1960 AIEE paper that "The selection of a satisfactory level of reliability or a corresponding index appropriate to any methods of measurement requires at some point an exercise of informed judgement".

This comment is as applicable to the determination of an appropriate capacity reserve margin using a value based reliability assessment approach, as it was to the determination of the LOLP index of one day in ten years over fifty years ago.