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INTRODUCTION

1.1 OVERVIEW OF TRANSMISSION PLANNING

1.1.1 Basic Tasks in Transmission Planning

The fundamental objective of transmission planning is to develop the system as economically as possible and maintain an acceptable reliability level. The system development is generally associated with determination of a reinforcement alternative and its implementation time. A decision on retirement or replacement of aging system equipment is also an important task in planning.

There are many drivers for the development of a transmission system, and these mainly include

- Load growth
- New-generation sources
- Equipment aging
- Commercial opportunities
- Changes in export to and import from neighbor systems
- Variations in supply reliability requirements of customers

Probabilistic Transmission System Planning, by Wenyuan Li

- Access of new loads or independent power producers (IPPs)
- New wheeling requirements

Most transmission development projects are driven by the first three factors: load growth, new-generation sources, and equipment aging. Traditionally, a utility company was vertically organized. Generation, transmission, and distribution were owned and therefore planned by a single company. Generation and transmission have been unbundled in most countries since the deregulation of the power industry in the 1990s. In the deregulated environment, generation and transmission assets generally belong to different owners and thus are operated, planned, and managed separately by different companies. This book focuses on probabilistic planning of transmission systems, and the information on generation sources is treated as a known input.

Transmission planning can be divided into three stages in terms of timespan: long-term planning, medium-term planning, and short-term planning. *Long-term planning* is associated with a long period, such as 20–30 years. It often focuses on a high-level view of system development. The problems discussed in long-term planning are preliminary and may need significant changes or even redefinitions in subsequent planning stages because of very uncertain input data and information used. *Medium-term planning* can refer to a timeframe between 10 and 20 years. In this stage, preliminary considerations in long-term planning are modified according to actual information obtained in previous years, and study results are utilized to guide short-term projects. *Short-term planning* deals with the issues that have to be resolved within 10 years. Concrete alternatives must be investigated in depth and compared. Planning studies at this stage should lead to a capital plan for planning projects.

Transmission planning includes different tasks, such as

- Determination of voltage level
- Network enhancement
- Substation configuration
- Reactive resource planning
- Load or independent power producer (IPP) connection planning
- Equipment planning (spare, retirement, or replacement)
- Selection of new technologies [light high-voltage direct current (HVDC), flexible AC transmission system (FACTS), superconductive technology, wide-area measurement system (WAMS)-based technology]
- Special protection system scheme versus network reinforcement

A transmission planning project may be associated with one or more of the tasks listed above, and each task requires technical, economic, environmental, social, and political assessments. The technical assessment alone covers multiple considerations in space and time dimensions and requires numerous studies, which include load forecast, power flow calculation, contingency analysis, optimal power flow calculation, voltage and transient stability analysis, short-circuit analysis, and reliability evaluation. Essentially, the studies are operation simulations of future situations in many years. The purpose of the studies is to select and compare planning alternatives. It is necessary to identify which system situations can occur in the future and in which manner the transmission system can operate for each situation. The combinations of system states and operation manners will reach an astronomical figure. It is impractical to simulate all the cases. Obviously, some simplification is necessary in system modeling and selection of system states.

Transmission planning is an extremely complicated problem and is always broken into subproblems in system modeling. Coordination among subproblems is needed. The judgment of planning engineers and preselected feasible alternatives play an important role in coordination. Many optimization modeling approaches for transmission planning have been developed in the past. These approaches are merely techniques for solving one or more special subproblems. It is important to recognize that it is impossible to make a decision for a system reinforcement scheme based only on the result from a single optimization model. In fact, many constraints and considerations in environmental, social, and political aspects cannot be quantitatively modeled.

The load levels, network topologies, generation patterns, availability of system components, equipment ratings in different seasons, possible switching actions, and protection and control measures must be considered in selection of system states. There are two methods for the selection: deterministic and probabilistic. The traditional *deterministic* method has been used for many years. In this method, selection of system states relies on the judgment of planning engineers, and a planning decision depends only on consequences of selected system states. The *probabilistic* method is relatively new and has not been widely used yet in the planning practice of most utilities, although some efforts have been devoted to this area. A fundamental idea in the latter method is to stochastically select system states in terms of their probabilities of occurrence. Both probabilities and consequences of simulated system states are combined to create the results for a planning decision.

1.1.2 Traditional Planning Criteria

In order to ensure reliability and economy in system development, conventional transmission planning criteria have been established at a country, regional organization, or company level. The famous NERC (North American Electric Reliability Corporation) reliability standard [1] is a good example. It includes the following sections:

- BAL—resource and demand balancing
- CIP—critical infrastructure protection
- COM—communications
- EOP—emergency preparedness and operations
- FAC—facilities design, connections, and maintenance
- INT—interchange scheduling and coordination
- IRO—interconnection reliability operations (and coordination)
- MOD—modeling, data, and analysis
- NUC—nuclear

- PER—personnel performance, training, and qualifications
- PRC—protection and control
- TOP—transmission operation
- TPL—transmission planning
- VAR—voltage and reactive power

It can be seen that this standard covers a wide range of areas and is beyond transmission planning. However, it is important to appreciate that the criteria for transmission planning are not only limited within the TPL section but should also be associated with the sections of BAL, FAC, MOD, PRC, TOP, TPL, and VAR.

The contents of conventional transmission planning criteria should at least include, but not be limited to, the following aspects [1–3]:

1. *Deterministic Security Principle.* This basically refers to the $N-1$ principle. The $N-1$ criterion means that a transmission system must have a sufficient number of elements to ensure that the outage or fault disturbance of a single element in any system condition does not result in any system problem, including overloading, under- or overvoltage, disconnection of other components, unplanned load curtailment, transient instability, and voltage instability. The NERC criteria also include performance requirements for planning conditions associated with two or more element outages. However, only very few important multielement outage conditions can be assessed in actual practice since the number of such conditions is too large.
2. *Voltage Levels.* The voltage level is often chosen as the one in the existing system as long as it can provide required power transfer capability without incurring unreasonable losses. Where existing voltages do not provide the required capability at a reasonable cost, a new voltage level may be established on the basis of technical and economic analyses.
3. *Equipment Ratings.* Equipment ratings (including normal and emergency ratings) are essential inputs in planning and are generally specified in manufacturer designs or industry standards. The equipment in a transmission system includes transmission lines, underground or submarine cables, transformers, instrument transformers, shunt and series capacitors, shunt and series reactors, circuit breakers, switches, static VAR compensators (SVCs), static synchronous compensators (STATCOMs), HVDC devices, bus conductors, and protection relays.
4. *System Operating Limits.* In addition to equipment ratings, system operating limits are also essential inputs in planning and include limits on voltage, frequency, thermal capacity, transient stability, voltage stability, and small-signal stability. The limits are divided into two categories for pre- and postcontingencies, and are expressed in different measure units, such as megawatts (MW), megavolt-amperes reactive (MVAR), amperes, hertz, volts, or a permissible percentage. The violation of a system operating limit may cause a consequence of instability, system split, or/and cascading outages.

5. *Transfer Capability.* Transfer capability is the amount of electric power that can be moved on a cut-plane between two areas under a specified system condition. A cutplane is often a group of transmission lines. This is associated with two terms: total transfer capability (TTC) and available transfer capability (ATC) [4]. The latter can be determined by

$$\mathrm{ATC} = \mathrm{TTC} - \mathrm{TRM} - \mathrm{CBM} - \mathrm{ETC}$$

   where TRM (transmission reliability margin) is the transfer capability margin required to ensure system security under a reasonable range of uncertainties and possible system conditions, CBM (capacity benefit margin) is the transfer capability reserved to ensure the access to generation from interconnected areas to meet generation reliability requirements, and ETC (existing transmission commitment) is the transfer capability scheduled for transmission services. Obviously, determination of TTC and ATC is associated with not only thermal but also stability limits.
6. *Connection Requirements.* As transmission system open access becomes a reality with deregulation in the power industry, various interconnections to a transmission system have greatly increased. These include the connections of generation, transmission, and end-user facilities. The term *generation facilities* refers to not only generators of generation companies but also regular IPPs and renewable sources. The connection projects require considerable feasibility, system impact, and facility studies, which have naturally become parts of transmission planning activities. The connection requirements are not only related to technical studies but also heavily associated with regulatory policies and business models.
7. *Protection and Control.* In some cases of transmission planning, a protection and control scheme can ensure system security while avoiding addition of primary equipment, resulting in a considerable saving of capital investment. In addition to traditional equipment protection and control schemes, the special protection system (SPS) and wide-area measurement system (WAMS) play a greater role in system security. The SPS, which is sometimes called a *remedial action scheme* (RAS), includes different schemes such as undervoltage load shedding, underfrequency load shedding, auto-VAR control, generation rejection, line tripping, and transient overvoltage control [5]. All the SPS schemes must meet reliability requirements and design principles. The WAMS, which can be also called a *wide-area control system* since its function is not limited to measurement, has been rapidly developed and applied in recent years. However, the reliability criteria for WAMS have not been well established so far.
8. *Data and Models.* All planning studies require adequate and accurate data and models, including those for static and dynamic simulations in both internal and external representations. The data and models for loads, generation sources, and customer connections need the coordination between transmission companies and their customers. The requirements of data management, including

validation, database, and historical data analysis, are essential to transmission planning.

9. *Economic Analysis Criteria.* Generally, more than one system alternative meet the technical planning criteria, and therefore economic analyses are conducted to select the least total cost alternative. The total cost includes capital and operating costs. In traditional planning, unreliability cost is not a component of economic analysis. The cost analysis must be carried out in a planning period of many years. Because of the unpredictability of economic parameters for the future, it is often necessary to perform sensitivity studies to examine the effects of parameter variations.

1.2 NECESSITY OF PROBABILISTIC TRANSMISSION PLANNING

The purpose of probabilistic planning is to add one more dimension enhancing the transmission planning process rather than to replace the traditional criteria summarized in Section 1.1.2. The majority of the traditional criteria will continue to be used in probabilistic planning with the exception of the following new ideas:

- The $N - 1$ principle is no longer a unique security criterion. In addition to single contingencies, multicomponent outages (as many as possible) have to be considered.
- Not only the consequences but also the occurrence probabilities of outage events must be simulated.
- Uncertainties in network configurations, load forecast, generation patterns, and other parameters should be represented as possible using probabilistic or/and fuzzy modeling methods.
- On top of the traditional studies (power flow, optimal power flow, contingency analysis, and stability assessment), the probabilistic techniques (probabilistic power flow, probabilistic contingency analysis, and probabilistic stability assessments) should be conducted. In articular, probabilistic system reliability evaluation is performed and becomes a key step.
- Unreliability cost assessment is a crucial part of overall economic analysis and plays an important role in planning decisions. Introduction of the unreliability cost, which depends on various probabilistic factors, establishes a probabilistic feature in economic analysis. The uncertain factors in economic parameters can also be considered.

There are numerous reasons for doing probabilistic transmission planning [6–8]:

1. One major weakness of deterministic criteria is the fact that the probabilistic nature of outage data and system parameters is overlooked. For instance, an outage event, even if extremely undesirable, is of little consequence if it is so

unlikely that it can be ignored. A planning alternative based on such an event will lead to overinvestment. Conversely, if selected outage events are not very severe but have relatively high probabilities of occurrence, an option based only on the effects of such events will still result in a high-risk outcome. Probabilistic planning can recognize not only the severity but also the likelihood of occurrence of events.

2. The deterministic criterion is based on the worst-case study. The "worst case" may be missed. For example, system peak load is generally used as one of the worst conditions. However, some serious system problems may not necessarily occur at peak load. Also, even if a system withstands the "worst case," the system is still not risk-free. It is worthy to identify the risk level associated with the $N-1$ criterion. This is one of the tasks in probabilistic transmission planning.
3. Major outages are usually associated with multiple component failures or cascading events in real life. This suggests that the $N-1$ criterion is insufficient to preserve a reasonable level of system reliability. However, on the other hand, it is almost impossible for any utility to justify the $N-2$ or $N-3$ principle for all outage events in transmission planning. A better alternative is to bring risk management into planning practice and keep system risk within an acceptable level.

There is no conflict between deterministic and probabilistic planning criteria. A complete system planning process includes societal, environmental, technical, and economic assessments. Probabilistic economic assessment and reliability evaluation are suggested to add as a part of the whole process. Figure 1.1 gives a conceptual example in which seven candidates for planning alternatives are assumed at the beginning. Two

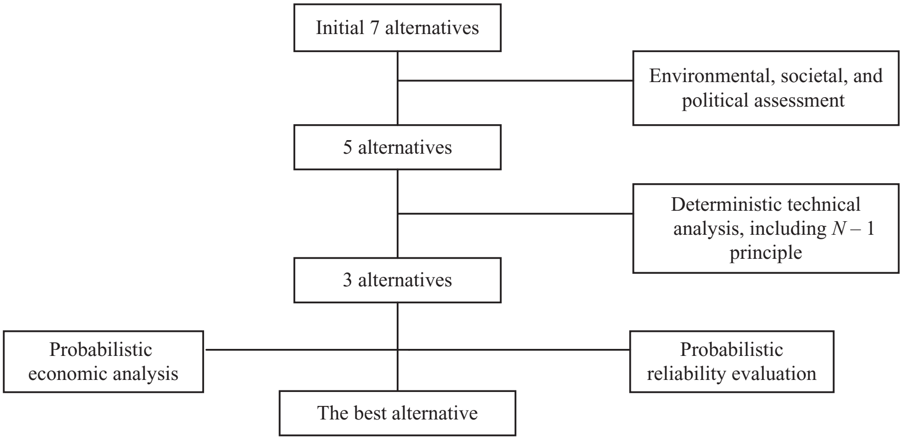

Figure 1.1. System planning process.

of them are excluded on the basis of environmental, societal, or political considerations. Deterministic technical criteria including the $N - 1$ principle are applied to the remaining five alternatives. Two more alternatives are eliminated from the candidate list because of their inability to meet the deterministic technical criteria. Then probabilistic reliability evaluation and probabilistic economic analysis are performed to select the best scenario. Both the $N - 1$ principle and probabilistic reliability criteria are satisfied. Other probabilistic techniques can also be applied to system analyses even in the domain of deterministic criteria.

Although the majority of the traditional criteria are still effective in probabilistic planning, introduction of the probability-related ideas (particularly the concept of unreliability cost) will significantly change the planning process and the philosophy in decisionmaking. Probabilistic transmission planning brings the missed (overlooked) factors in the traditional planning into studies and will definitely lead to a more reasonable decision in the sense of a tradeoff between reliability and economy.

1.3 OUTLINE OF THE BOOK

The book can be divided into four parts. The first part includes Chapters 2–7, which discuss the concepts, models, methods, and data that are used in probabilistic transmission planning. Chapter 8, as the second part, focuses on a special issue—how to deal with the uncertainty of data in probabilistic planning using fuzzy techniques. The third part, Chapters 9–12, addresses four essential issues in probabilistic transmission planning using actual utility systems as examples. The fourth part consists of three appendixes, which provide the basic knowledge in mathematics for probabilistic planning.

Chapter 2 presents the basic concepts of probabilistic transmission planning emphasizing the criteria and general procedure.

Chapter 3 addresses load modeling issues in both time and space perspectives. Load growth is a major driver in transmission planning. Various practical load forecast methods are discussed. Other aspects of load modeling include load clustering, uncertainty, and correlation of bus loads, as well as voltage and frequency characteristics of loads.

Chapter 4 focuses on system analysis techniques. The traditional analysis methods, which are still required in probabilistic transmission planning, are briefly summarized. These include power flow, optimal power flow, contingency analysis, and voltage and transient stability assessments. Probabilistic power flow, probabilistic optimization techniques, and risk-index-based contingency ranking are presented as new analysis methods.

Chapter 5 illustrates transmission reliability evaluation. This is a key step toward probabilistic transmission planning. Reliability indices and reliability worth assessment are explained. In the adequacy perspective, reliability evaluation methods for composite generation–transmission systems and substation configurations are discussed. In the security perspective, probabilistic voltage and transient stability assessments are proposed as new techniques. This chapter only provides a summary of the topic; more details can be found in the author's previous book, *Risk Assessment of Power Systems*, in the same IEEE Press Series on Power Engineering.

Chapter 6 discusses the methods for economic analysis, which is another key in probabilistic transmission planning. Three cost components for planning projects are outlined. Following the basic concepts on time value of money and depreciation methods, the economic assessment techniques for project investment and equipment replacement are presented in detail. A probabilistic method for the uncertainty of economic parameters is also proposed. Compared to books on engineering economics, a major feature is that the unreliability cost is incorporated in the proposed techniques.

Chapter 7 addresses data issues in probabilistic transmission planning. The data for system analysis include equipment parameters, ratings, system operation limits, and load coincidence factors. Preparing reliability data is an important step toward probabilistic planning. Both equipment outage indices and delivery point indices, which are based on outage statistics, are discussed with typical examples. Other data required in planning are also outlined.

Chapter 8 proposes a solution to data uncertainty in probabilistic transmission planning using combined fuzzy and probabilistic techniques. The uncertainty includes both randomness and fuzziness of loads and outage parameters, particularly for the data associated with weather conditions. Two examples for reliability assessment are provided to demonstrate applications of the techniques presented. Similar ideas can be extended to the uncertainty of other data and other system analyses.

Chapters 9–12 are devoted to practical applications that are day-to-day topics in transmission planning. The special concept, method, and procedure for each topic are developed, and actual planning examples from real utility transmission systems are provided. In particular, the results in the applications have been implemented in the utility's decisionmaking.

Chapter 9 discusses transmission network reinforcement planning. This is a task that transmission planners have to deal with every day. Two applications are developed using probabilistic planning methods. One is the reinforcement of a bulk power supply system; the other is the comparison among planning alternatives for a regional transmission network.

Chapter 10 copes with retirement planning of system components. The retirement timing of a system component is a challenge facing planners as a transmission system ages. New probabilistic planning methods are presented for two applications: (1) the retirement of an AC cable and (2) the replacement strategy of a DC cable.

Chapter 11 discusses substation planning. There are two types of problems in substation planning. One is selection of substation configuration; the other is determination of the number and timing of spare equipment shared by substations. Probabilistic approaches to both problems are established and demonstrated using actual utility application examples.

Chapter 12 is committed to the probabilistic planning method for radial single-circuit supply systems. This is a challenging issue that cannot be resolved using the traditional $N - 1$ planning criterion. The method presented is based on historical outage indices and probabilistic economic analysis with predictive reliability evaluation. A utility example is provided.

There are three appendixes. Appendix A provides the basic concepts in probability theory and statistics, whereas Appendix B presents the elements in fuzzy mathematics. Appendix C gives the fundamentals in reliability evaluation, including both crisp and fuzzy reliability assessment methods.

Transmission planning covers a very wide range of topics. The book does not pretend to include all known and available materials in this area. The intent is to focus on the basic aspects and most important applications in probabilistic transmission planning.