

Time-horizons in the planning and operation of transmission networks

An overview

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Time-horizons in the planning and operation of transmission networks: an overview

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Abstract: In the planning and operation of power systems, actions are taken in different processes and time-horizons. The purpose of these actions is to secure a high reliability level. Although the three main processes (grid development, asset management, and system operation) are described in literature, there has been no explicit study on the time-horizons (long-term, mid-term, and short-term) and actual time-scale (decades, years, months, etc.) that these processes focus on. This study aims at making a review of the various activities performed by transmission system operators while reviewing the concept of each time-horizon and methodologies developed in literature. As decisions taken in different time-horizons can influence each other, the interactions and overlapping are discussed.

1 Introduction

Today's scenario places tremendous stress on transmission and distribution (T&D) assets because of:

- Development and increase in electricity demand.
- Structural changes [more interconnections, intermittent renewable energy sources (RES), flexible AC transmission systems (FACTS), high voltage direct current (HVDC), and other power electronics-based devices].
- New operating policies like liberalisation of the energy market, more intense trading, coupled markets, higher demand-side participation.

This has led the power system reliability specialists to divide their activities into three main processes in which sets of decisions are taken. These activities are usually divided into the processes [1]:

- (i) Grid development (long-term).
- (ii) Asset management (AM) (mid-term).
- (iii) System operation (short-term).

However, in reality under each of these three main processes, various sub-activities are performed on different time-horizons as illustrated in Fig. 1. The actual time scale of these horizons can vary between different processes and has never been clearly mentioned in any published literature, which can lead to confusion in practice. For example, long-term grid development is performed on a time scale of decades, while long-term system operation has a time scale of weeks/months as shown in Fig. 2. It is the primary scope of this paper to clarify this by bringing together the concept of different time-horizons in one survey, while embedding the various literatures as support. Furthermore, recent developments in the different time-horizons are discussed, as well as the overlapping between activities.

Discussion on planning and operation brings 'reliability' into picture. Power system reliability has been a subject of interest since the 1960s when Billinton and Bollinger [2] published the first article in 1968. Since then, there has been a huge amount of research introducing various methods and theory to pursue reliable power system operation. Besides, Billinton and other authors have made significant bibliographic studies about the probabilistic models in different periods. Some of these are Schilling *et al.* for

the period 1962–1988 in 1990 [3], Billinton in 1972 [4], Allan *et al.* for 1987–1991 in 1994 [5], and Billinton *et al.* for 1996–1999 in 2001 [6]. Schilling *et al.* [7] made a comprehensive bibliographic study of probabilistic security analysis for the period 1968–2008 which included 521 articles in a 40-year range. In the past three decades, a variety of achievements have been accomplished on the concepts, models, algorithms, software and applications of power system reliability [8–10]. Reneses *et al.* [11], for the first time, discussed the importance of coordination among the time-horizons, stating how long-term decisions impact short-term decisions.

This paper is organised as follows. Section 2 focuses on the concept of different time-horizons, and lists the different methodologies developed in various literatures. Section 3 discusses the overlapping and interactions among the time-horizons, the possibilities for a combined reliability approach, and the challenges for the future. This section also concludes the literature survey.

2 Review of three main processes

In this section, the three main processes and time-horizons are discussed. Fig. 2 was created to understand the concept of three processes and horizons. It gives an overview of the activities that are performed in each process and time-horizon, and shows the actual time scale of these activities. The next sub-sections describe each of the processes in detail, supported by methods and tools published in various literatures.

2.1 Grid development

Grid development aims mainly at transmission system expansion planning. According to Pereira *et al.* [12], grid development can be divided into two parts:

- Determining optimal investments in new system capacity.
- Determining system operating cost and supply reliability associated with the construction of this new capacity.

In short, developing the transmission infrastructure is one of the key priorities. An adequate transmission network is responsible for a safe, reliable, and efficient delivery of electrical energy to the

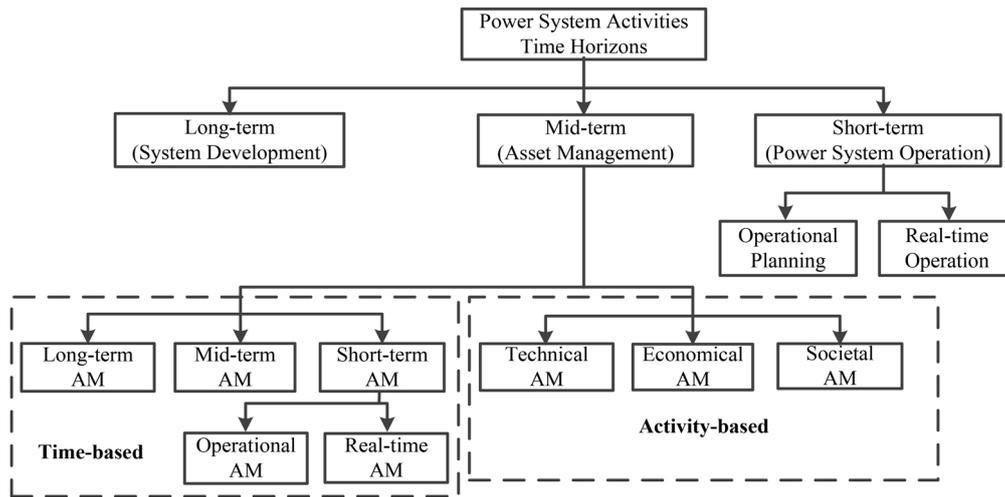


Fig. 1 Classification of time-horizons according to literature

consumers. Thus, grid development aims at providing solutions for future. For an efficient planning, it is important to find the type, location, and timing of the network upgrades not only at a minimal cost but also considering socio-economic, environmental, reliability, legal, and political constraints. Since the fact that it generally covers the far future, grid development deals with a large number of uncertainties in various domains.

In practice, grid development is performed on longer and shorter time-horizons. *Long-term grid development* has a time scale of decades and includes the creation of grid expansion plans based on load/generation scenarios. In *mid-term grid development*, investments in the grid infrastructure (new connections, substations, etc.) are made. In *short-term grid development*, only small modifications of the network are made in the time scale of months. New protection systems, phase shifters, and so on can be installed in this time-horizon.

Literature survey, in the last four decades, reveals that transmission system expansion planning has evolved due to introduction of various mathematical models and techniques. In the recent period, Lattore *et al.* [13] in 2003, Lee *et al.* [14] in 2006, and Hemmati *et al.* [15, 16] in 2013 presented an extensive list of different models and tools used in transmission expansion planning. Thereafter, there has been no explicit study on this topic though Kishore and Singhal [17] did a review of transmission line planning in 2014. Basically, in grid development, stochastic studies have so far indicated very helpful in various studies [18–24]. Hobbs [25], in 1994, enlisted the use of optimisation methods to tackle planning horizon in electric utility. It can be

deduced that mathematical modelling for grid development is a challenging task because of the presence of so many constraints and a high level of uncertainty.

In the last three decades, there have been ample amount of work done in this context. A brief study about the techniques, algorithms, and concepts already developed are (*though a many could not be cited due to the scope of this paper*) as follows: maximum principle [26], mixed-integer programming [27–31], linear and dynamic programming [12, 32–34], disjunctive mixed integer programming [35], branch and bound algorithm [36], implicit enumeration [37, 38], Benders decomposition [12, 39, 40], maximum flow [12], hierarchical decomposition [41], sensitivity analysis [42, 43], genetic algorithm (GA) [44–49], object-oriented programming [50], game-theory [51–54], simulated annealing [55, 56], expert systems [57, 58], fuzzy set [49, 59, 60], greedy randomised adaptive search [61], non-convex optimisation [62], tabu search [63], ant-colony [64], data-mining [65], particle swarm optimisation (PSO) [66–69], harmony search [70, 71], artificial neural network (ANN) [72], game theory [73], and robust optimisation techniques [74–78].

In addition to the various tools and methods, there is an immense requirement of tools and knowledge-based schemes for decision making to integrate RES under market regulations and uncertainties [79, 80]. This is a challenging task because of stochastic behaviour, non-linearities, and non-convexities [62] of RES. At the same time, the electricity market also adds to the uncertainty [81]. It can be deduced that risk and uncertainties have evolved due to advancement in technology, and will be evolving

		Time Horizons				Time Scale
		Long-Term	Mid-Term	Short-Term	Real-Time	
Main Processes	Grid Development	Onshore/offshore grid expansion plans (based on generation/load scenarios)	Investments in new grid components (connections, substations, etc.)	Small modifications of the grid (new phase shifters, protection systems, etc.)	---	←Decades ←Years ←Months ←Weeks ←Days
	Asset Management	Refurbishment, replacement and up-gradation plans of existing assets	Maintenance scheduling, allocation or resources	Repair and condition monitoring of assets	Condition monitoring, outage management	←Hours
	System Operation	Operational policies	Day-ahead planning	Hour-ahead planning, preventive control actions (redispatch, transport restrictions, cancelling maintenance)	Corrective control actions (redispatch, switching actions, wind/load curtailment)	←Minutes

Fig. 2 Actions taken during different time-horizons

further. For instance, some of the novel emerging/prominent approaches for expansion planning are based on least-effort criterion [82], maximum principle [26], minimising the maximum regret or maximising benefits [83], uncertainties [84], and security constraints [85]. Moreover, there are also environmental concerns when RES are considered. Correa *et al.* [86] did a comprehensive study of the impact of transmission expansion planning on environmental conditions. To cite an example, external factors like emission constraints [87, 88], efficiency measures, pollution control, and other environmental policy greatly influence grid development.

2.2 Asset management

Asset management, termed as mid-term horizon, is defined as the process of maximising the return on investment of equipment over its entire life cycle by maximising performance and minimising costs (both capital expenditure and operational expenditure) at a given risk level [89]. In the power industry, T&D components are capital-intensive assets and there is a requirement of utilising them in the most efficient way. Since the late 1990s, the power industry has been substantially deregulated, which gave birth to ‘asset management’.

AM is closely related to grid development and system operation, hence forms a bridge between the long-term and short-term horizons. CIGRE WG D1.17 [90] shows how AM relies on asset data and information extracted from this data that is used in future planning. Accurate, timely, and reliable asset information results in better decisions and in the past, there has been much research on various aspects of AM [91–94].

As seen in Fig. 1, AM can be classified based on time domain and activity domain. The time-domain AM is categorised into long-, mid-, and short-term:

- *Long-term AM*: The time frame ranges from a year and beyond and it aims at replacement, refurbishment or up-gradation of existing assets like phase-shifting transformers, reactive devices, and existing connections. This involves greater financial risks, and hence proper planning can avoid the risks involved in time delays, interest rates, and long-term load diversity.
- *Mid-term AM*: The time frame ranges a few months and it mainly involves optimal scheduling of equipment maintenance to extend the life span of existing facilities and to prevent unplanned outages. Maintenance costs are the driving factor since it is a function of outages (both planned and unplanned), and can be greatly reduced when planned outages are scheduled according to the availability of resources during seasonal load distributions.
- *Short-term AM*: Short-term AM is categorised into operational AM (daily/weekly) and real-time AM. Operational AM aims at minimising risks involved with assets, both physical and financial, due to load demand. Real-time AM is also called asset outage management. Contingency analysis forms a vital part. It helps in assessing the effect of unexpected outages due to changes in weather conditions, any sudden breakdown or load fluctuations on the asset condition and performance. In recent times, due to technological advancements, real-time monitoring of assets is possible.

On the basis of activity aspect, Smit *et al.* [93] categorise AM into technical-, economical-, and societal-AM. Technical AM deals with ageing, insulation, and other physical conditions of assets. Socio-economic aspect is broken down to individual aspects, which deal with how AM would be influenced by financial constraints and eventually its impact on society.

As seen from the above classification, maintenance forms the crucial part of AM. Literature survey shows there have been explicit studies on maintenance of various power system components, like power transformers, overhead lines, cables, and protection devices [95–103]. With the integration of RES, wind farms have been extensively studied from AM point of view in [96, 97, 104–107]. Suwanasri *et al.* [108] studied a zero-profit

method for up-gradation of high-voltage equipment in a substation, i.e. power transformers, current transformers, voltage transformers, high-voltage circuit breakers, switches, and surge arresters. In general, the power transformer represents ~60% of the overall costs of the network, and is ranked as one of the most important and expensive components [109]. Study reveals about substantial research on power transformers in various literature about health monitoring, ageing, and oil indicators [110–115]. Similarly, studies have been carried out for overhead lines [115–118], underground cables [115, 119, 120], and circuit breakers [115, 121–124]. Yoon and Teo [125] presented a real-life case study on AM in Singapore though it focused on underground grids. With the advent of computational tools, information technology (IT), and human-machine interface in the last decade, Kostic [126, 127] made studies on the application of IT in AM while focusing on energy management services.

Various computational models and optimisation techniques have been developed for maintenance, refurbishment, ageing, and monitoring techniques in AM, like state diagram [128], fuzzy technique [105, 113, 129], ANN [109], PSO [106], linear programming [118, 130], branch and bound technique [131], and other optimisation techniques [132, 133].

2.3 System operation

System operation encompasses real-time operation and operational planning, which deals with activities ahead of real time. The duration of this time-horizon ranges from minutes/hours to several days ahead, though this can vary between different transmission system operators. Reliability is of primary concern and it is very important to maintain both security and adequacy levels at the acceptable levels with minimum socio-economic cost. System security level refers to the ability of the system to response to failures [8, 10]. This ensures that the dynamics induced from any contingency or any operating conditions remain within acceptable level. System adequacy indicates whether there are enough means in the system to fulfil its function, also during contingencies. A detailed analysis of the two sub-levels is performed:

- *Operational planning*: Operational planning happens at several instances prior to the establishment of the system operating conditions. It constitutes the preparatory phases before real-time operation. Also, operational planning ensures that right decisions are taken in advance such that reliability management is achievable within a prolonged future period of time, called the operational planning horizon. The horizon consists of a sequence of target real-time intervals. The operational planning time-horizon does not have a specific point in time, it can be week-ahead (W-1), two days (D-2) or one day (D-1) in advance as well as several (n) hours (H- n) before real time. Due to the unspecific points in time, operational planning brings few uncertainties into consideration.
- *Real-time operation*: Real-time operation encompasses system operation for time intervals ranging 15–60 min. During this time interval, it is assumed that the system operating conditions (scheduled generation, demand, inter-area exchange, and network configuration) are highly predictable. Fig. 3 shows the inter-dependency of real-time operation and operational planning. Real-time operation is a series of activities, which are planned in a sequential manner. It starts with the preventive control, with a horizon of 1–2 h, and aims operation at optimal cost under security constraints. Preventive action is always planned and covers failures or unexpected reactions from the system point of view. Taking preventive decisions such as switching equipment, rescheduling loads, is also part of the sequence. Furthermore, it oversees contingencies, and prepares or adjusts the system to take control decisions. Preventive control may be followed by two other control strategies, namely corrective control and emergency control. Corrective control is the first step taken following preventive control. The horizon is 0–15 min, and aims at maintaining the system intact. Emergency action is the control

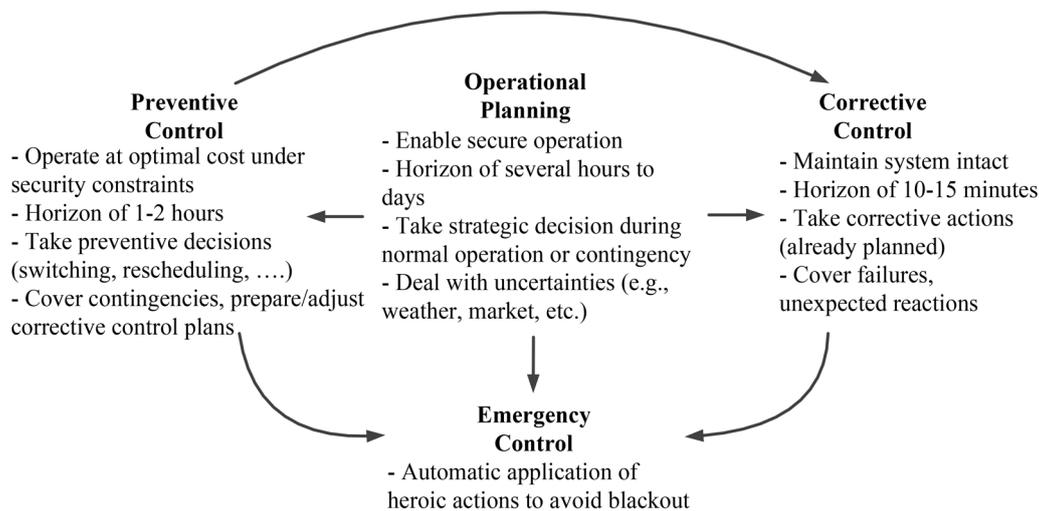


Fig. 3 Actions taken during short-term operational planning

scheme of real-time operation. Both preventive as well as corrective action may end up in emergency action in the worst-case scenario. Emergency action is taken during any unplanned contingency or failure when the effect of a contingency is not sufficiently covered by means of preventive and corrective actions.

Literature study reveals comprehensive methodologies for preventive and corrective actions. Load shedding, considered as corrective action, is verified in various literatures [134–138]. Other various mathematical modelling and optimisation techniques include: PSO [139], decision trees [140–145], model predictive control [146], ant colony system [147–149], GA and ANN [150], differential evolution [151, 152], and various other optimisation techniques [153, 154].

In system operation, decisions are taken within a limited time. Probabilistic risk analysis is already often used in grid development, but the application in system operation is relatively new. IEEE and CIGRE have developed task forces working on risk analysis and probabilistic techniques for planning and operation [155, 156]. Recently, various domains in risk-based planning have been studied, like power transfer limit [157], weather conditions [158], stability [159], and reserve generation [160]. Preece and Milanovic [159] combined probabilistic and fuzzy inference systems to categorise different degrees of risk,

which facilitates the understanding of the planner. The paper focuses on stability issues and the methodology was applied to a multi-area network, but the concept can also be applied to reliability problems. Ciapessoni *et al.* [161] studied the advantages of integrating probabilistic and deterministic tools for enhancing security during short-term horizon.

3 Conclusions

This paper reviewed the concept of different main processes and time-horizons in the planning and operation of power systems. The authors have tried their best to encompass adequate theory with supporting literature for the different time-horizons. Not only in terms of time scale but also the tasks involved in each of the time-horizons make them different from each other. In some cases, short-term planning may work out efficiently, but it may not be adequate in identifying the long term needs of the system. For example, in the short term, a lower voltage and less expensive line addition may be adequate but may require an expensive upgrade within a decade. In contrast, an initially more expensive and higher capacity line might be less expensive in the long term.

There is always an overlap among the different processes, as illustrated in Fig. 4. Without discussing this overlap, the work

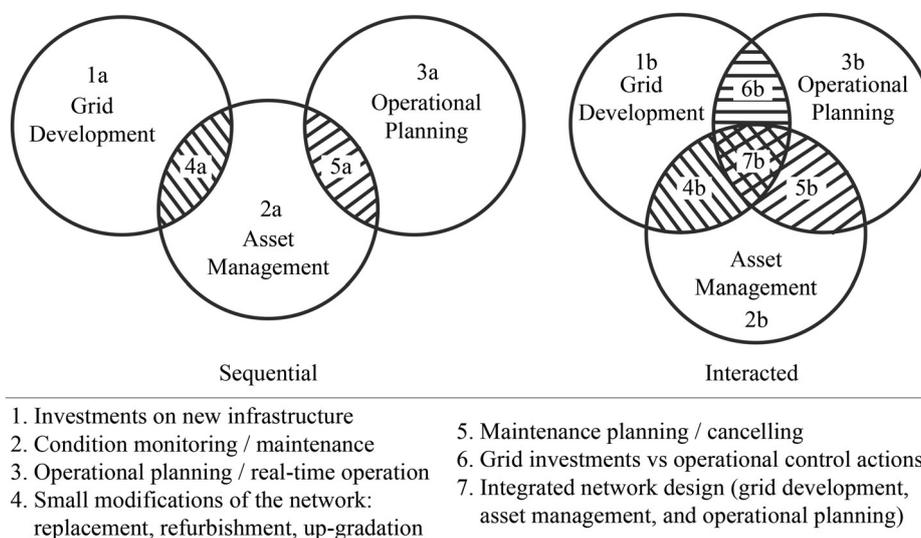


Fig. 4 Interactions among the three processes

Table 1 Future (possible) challenges due to interaction of different time-horizons

Challenge	Description
uncertainty modelling	modelling the variability of RES, market uncertainties, variable demand, high-impact-low-probability events, operating conditions, contingency modelling
data management tools	handling large amounts of data, collecting suitable failure statistics of network components develop complex methods in academia for easy understanding and use in the real life. Risk analysis of large-scale systems with large amount of uncertainties within a reasonable computing time
result interpretation	presentation of the results of probabilistic reliability analysis in clear, understandable and actionable indices

would be incomplete. Small modifications of the network can be required because of grid development or because of AM (area-4a in Fig. 4) and planned maintenance might be cancelled during system operation because of a contingency (area-5a). In the past, the three processes consisted of more or less separate activities. This is illustrated as a sequential approach in Fig. 4. For example, the Dutch 380 kV ring was developed considering $n-2$ ($n-1$ during maintenance) redundancy (area-1a). As a result, this gave enough room to plan maintenance in AM (area-2a), and enough room for operational activities (area-3a). In the future, the overlap and interaction between the three main processes is expected to increase, because of the developments as mentioned initially in this work (also refer Fig. 4 for interacted approach). Earlier studies showed that offshore network redundancy is mostly uneconomical [162]. Onshore spinning generation reserve can serve as redundancy for the offshore network to maintain a high level of reliability of supply (area-6b in Fig. 4). If redundancy is not created in the offshore network (long-term activity), this has consequences for activities in other time-horizons.

Several (possible) challenges can be expected for future as enlisted in Table 1. Uncertainty modelling is one of the primary challenges followed by big data. The management of large amount of data poses a second challenge. Furthermore, the development of new risk tools and clear interpretation of results are of importance, as risk analysis is useless if the results cannot be translated into actions. Various projects on pan-European electric power system are working towards improving reliability or developing a new reliability criterion. Vefsnmo *et al.* [163] in AFTER project (<http://www.after-project.eu>) are developing risk assessment tool to be used in short-term horizon. GARPUR project (<http://www.garpur-project.eu>) aims at developing new reliability criteria taking into consideration the three time-horizons (<http://www.garpur-project.eu/deliverables>). As transmission system planners face numerous challenges originated in load growth, economic forces of deregulation, and development and integration of new technologies, this paper presents recent literatures to keep up with the advancement.

In the end, the authors would like to state that large number of articles could not be cited in this paper since citing all would be out of scope of this paper. For a clear picture of recent developments, a table of publication listing in the last four decades is shown in Table 2. From the table, it can be noted that the work has focused on literatures published in the last 10 years, thus presenting the recent state-of-art methodologies.

Table 2 Publication listing

Time frame	Number of publications
2006–2015 (present)	103
1996–2005	40
before–1995	20

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