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Implications of short-term renewable energy resource intermittency in long-term power system planning

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ABSTRACT

Power system operational uncertainties of load fluctuation, and unplanned outage of generating units, or lines are normally handled by reserve generation or transmission capacity. The output of conventional generators is quite controllable, and load variation is predictable within a certain confidence limit. On the other hand, output of variable renewable generators is random and uncontrollable. Large-scale integration of these resources introduces additional uncertainty to an existing system. This drastic change in generation paradigm underscores the need for additional flexible capacity to maintain reliable system operation. Conventional long-term planning studies tend to overestimate system's ability to integrate renewable energy and underestimate flexibility requirement due to inherent modeling limitations. Mathematical models that are used in these planning exercises adopt simplified spatial and temporal resolution and often neglect real system operation. Therefore, there is an urgent need to develop new planning strategies to reflect short-term renewable energy resource intermittency in long-term decision making. In this article, the implication of RE intermittency in system operation and also their impact on long-term planning is discussed. Recent planning approaches from literature which aim to address these issues, have been highlighted. A critical discussion regarding their usefulness is also presented.

1. Introduction

Concern for climate change and energy security has brought global consensus over the need to adopt new strategies for power generation, transmission, and utilization. Power production using fossil fuels, such as coal, has been one of the largest contributors to global net greenhouse gas emissions (approximately 25%) [1]. Therefore, decarbonization of power sector is one of the key agendas of current century [2]. Renewable energy (RE) sources (*e.g.* solar, wind) have evolved as the most attractive options in this regard as they are clean, secure and sustainable, compared to other options such as nuclear energy. It is expected that new policy mechanisms and market structures will ensure large-scale penetration of RE in global as well as various national energy systems [3–6].

Among various RE resources, global policy interests are mostly focused on solar and wind for power generation. The main challenges associated with these resources are their variability and uncertainty in spatial and temporal scale. Due to this, grid operators have little control over the output from these intermittent RE power plants, and cannot schedule and dispatch them, as they do to thermal or hydro generators [7]. The uncontrollable generation from RE plants causes frequency and voltage fluctuation, leading to system imbalance and instability [8,9]. The penetration level of RE is dependent on the ability of residual system[1] to withstand associated imbalance and fluctuations. This implies that residual system should be able to respond to a sudden burst or loss of generation from RE generators, to maintain system balance and stability, *i.e.* it should be flexible[2] [10].

Identification of suitable flexible capacity is critical to ensure large-scale penetration of intermittent RE resources. Long-term energy system planning studies identify capacity required to meet certain policy targets and also a suitable pathway to provide optimal investment into that capacity. These studies often consider the whole energy system, *i.e.* all inter-connected energy sectors (transportation, agriculture, power, *etc.*). Current article focuses on power sector, as RE intermittency primarily jeopardizes power system operation. The models used in these exercises usually adopt coarse spatial and

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[1] The non-RE part of the existing system.
[2] Ability of a system to respond to the sudden uncontrollable changes imposed on it.

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temporal definitions and thus fail to address the effect of short-term RE resource variations on system operation. They often focus on capacity adequacy rather than quality of resource, and therefore, undervalue system flexibility need. An overhaul of strategies has become necessary so that they capture operational scale fluctuations. Maintaining consistency between short-term operational and long-term capacity planning is becoming crucial to identify optimum system portfolio.

A short description of power system structure, operation, and planning have been presented in Section 2. The implication of RE resource intermittency on system planning and operation has been discussed in Section 3. Section 4 discusses the need of considering flexibility in long-term system planning and its possible sources. Section 5 identifies the ability of various planning models to address long-term system flexibility need. In Section 6, approaches have been elaborated to show how short-term RE intermittency could be considered in long-term planning studies. Section 7 presents a comparison of these methods and finally, Section 8 concludes research findings.

2. Power system planning and operation

A power system comprises various interconnected entities like generators, transmission and distribution network, and load. Traditionally these entities within a particular geographical area were owned by a vertically integrated public utility. The planning, operation, and control of this kind of system were done by the same utility that owned it. Due to economic and operational inefficiencies of this monopolistic structure, deregulation and restructuring are being adopted to promote competitiveness and efficiency. In a restructured environment the ownership of power supply entities is distributed among different private or government players, regulated by a separate independent body. An electricity market is often designed for these players and customer to trade power, utilizing open access over the transmission network [11,12].

Power system planning can be classified as short-term, medium-term, and long-term. The short-term planning is associated with day-to-day system operation. Medium-term planning involves maintenance of system assets, while long-term planning relates to new capacity additions.

2.1. Short-term power system planning

Short-term power system planning involves scheduling generating units from day-ahead to week-ahead. The thermal generating units have several operating constraints such as minimum and maximum limits on generation, start-up and shut-down time, and ramp rates, which need to be considered at scheduling stage. These constraints together constitute a mixed integer optimization problem. System operators solve it to decide optimal commitment schedule. Due to reliability purpose, operators also need to maintain a certain amount of additional generating capacity in the form of spinning and non-spinning reserve. Spinning reserve is an extra capacity of already connected units after serving load and losses. Non-spinning reserves are units not synchronized to the grid but can be brought online within a small time frame. Spinning and non-spinning reserves together constitute total operating reserve of system [13,14].

Calculated schedules should lead to a secure system operation, *i.e.* system should withstand any contingency event such as failure of a generating unit. Consideration of security is crucial as in a large interconnected system; failure of a single component may drive cascading events leading to other equipment outage and ultimately system collapse. For analyzing system security, operators perform simulations considering contingent scenarios of dispatch, load, transmission capacity, *etc.* An optimal power flow problem is run in conjunction with contingency analysis to examine whether the strategies would satisfy thermal limits of transmission lines or not. The plans are revised if it appears to be insecure. Reliability standards dictate contingency criteria[3] operators need to maintain.

2.2. Power system operation

Grid operators monitor various operational parameters in real time to maintain system stability, security, and reliability. Generation levels of power plants, transmission line thermal limit, system frequency, bus voltage and angle, *etc.* are often critical parameters which operators need to maintain within a particular threshold to ensure reliable operation. Under normal operating conditions planned schedules should hold good with some revision based on updated load forecasts. During a contingency, operators need to implement a new plan immediately to rescue system out of emergency. The severity of contingency event depends on its location and system status. Unplanned outage of a small generating unit or intra-hour demand deviations is often handled by governor response and automatic generation control mechanisms of spinning reserves units. Additional non-spinning reserves are brought online or load shedding schemes are employed depending on the severity of generation outage. Daily load variation is quite predictable, and sudden loss of demand on a significant scale is uncommon, unless there is a transmission line loss. Line outage is often handled through additional transmission reserve margins or via alternate paths maintained for reliability purpose. During severe line outages, interconnected control areas coordinate by either reducing or increasing generation to relieve the contingency.

2.3. Medium-term power system planning

In timescale, medium-term planning resides between short and long-term planning and covers the tasks of creating maintenance schedules of generation and transmission equipment, fuel purchase, resource allocation and capacity contracting with other neighboring utilities, *etc.* Medium-term planning decisions are distinct from long-term planning in a sense that it only deals with existing resources compared to new capacity addition. Also, the medium-term decisions are set long before short-term dispatch planning. Midterm planning is highly relevant as, if supply assets are not maintained properly, they may fail under severe loading conditions. Also, knowledge of the yearly availability of supply assets is vital for short-term operational planning.

2.4. Long-term power system planning

Long-term planning studies are undertaken in extended time horizon (years to decades) covering future demand growth, technology or policy targets. They deal with upgradation of existing infrastructure or installation of new capacity which may be in the form of generators, transmission and distribution lines, *etc.* based on some policy inputs. They simultaneously identify quantity, type, year, and location of new capacity and also the corresponding cost of new investment. Planning studies of power utilities focus exclusively on the electricity sector, ignoring or aggregating the effects of other energy sectors. These studies are also often static, *i.e.* they analyze targeted future year in a single stage. On the other hand, national or regional level energy system planners take a dynamic approach by evaluating the solution for targeted year/s in multiple stages. They take an integrated overview of various energy systems at a time. The power sector is often studied as a part of the whole energy systems, though there are attempts to study it exclusively. Static planning is simpler and computationally easier

[3] The contingency criteria are often denoted as N-k; where N is the total number of the system component, and k is the number of equipment which has been failed. For example, N-1 contingency criterion implies that system should continue to operate even if a single component, may it be generating, transmitting or any other (the largest possible), fail.