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A composite metric for assessing flexibility available in conventional generators of power systems

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HIGHLIGHTS

- Novel framework to assess flexibility available from generators in power systems.
- Composite metric with appropriate weighting, normalization and aggregation methods.
- Sensitivity analysis demonstrates robustness of metric to methodological changes.
- Adaptive metric automatically adjusts to other generating units in power system.

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ABSTRACT

With increasing levels of integration of intermittent renewable energy in the power grid, it has become essential for power system planners to quantify future requirements of power systems in terms of *flexibility*. It is also equally important to evaluate whether the flexibility available in a given power system is adequate to meet more frequent and larger variations in the net load. In this paper, we present a novel framework to develop a composite metric that provides an accurate assessment of flexibility within conventional generators of a power system. This assessment is performed using eight technical characteristics of generating units as indicators. An Analytic Hierarchy Process is applied to assign weights to these indicators in order to reflect their relative importance in the supply of flexibility. Following normalization with min–max method, the indicators are linearly aggregated to give the composite flexibility index for each generator. The proposed methodology is tested on an adapted IEEE RTS-96 system. Our results demonstrate the consistency of the composite flexibility metric. It is further observed that the proposed metric is adaptive since it automatically adjusts to the addition and/or removal of generating units. To evaluate the robustness of the proposed framework, we also performed sensitivity and uncertainty analysis in the presence of alternative methodological choices in the composite metric construction process.

1. Introduction

In recent years, the growing integration of intermittent renewable energy sources (RES) in the power grid has emphasized the importance of flexibility in the reliable operation of power systems [1–3]. Flexibility refers to the ability of a power system to deploy its resources in response to changes in net load [4]. Net load is defined as the residual demand that must be supplied by conventional generation resources after all variable renewable energy generated has been used. Traditionally, power systems have been required to adjust their generation output in order to balance fluctuations on the demand side. However, load variations are predictable as their correlations with time and weather patterns are well understood. Consequently, they are reliably dealt with as long as the peak load is adequately met by the available generation capacity. As increasing shares of variable RES are integrated in a power system, the flexibility requirements become more severe [5]. Intermittent RES output not only varies considerably over short time spans but is also very difficult to predict accurately. These features increase the uncertainty and variability associated with the net load. While demand-side management, interconnection to neighboring power systems and energy storage facilities have the potential to contribute significantly to the overall flexibility of a power system, their impact in the medium term is expected to be limited [6]. In the foreseeable future, existing conventional generation resources will play a key role in effectively compensating more frequent net load fluctuations of higher amplitudes [6–8]. A power system composed mostly of insufficiently flexible generation resources will be typified by forced load shedding and

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curtailment of intermittent generation output [6,9,10]. As a result, it is critical for current power planning methodologies to account for generator operational characteristics that affect system flexibility [11–13]. Thus, power system planners must ensure that sufficiently flexible resources are available in the generation fleet to enable reliable operation of the power system under increased RES penetration. This emerging interest in power system flexibility has driven the development of metrics that provide an indication to operators about the inherent amount of flexibility they can call upon to balance generation and net load at all times. In particular, as will be shown, measures of the level of flexibility offered by individual generating units of a power system are found to be of greatest importance.

Assessing the flexibility available in power systems is a difficult exercise and has been the focus of active research recently [14]. A few metrics have been proposed to evaluate the availability of flexible resources in power systems. They vary in complexity, ranging from metrics that are derived from physical characteristics of the power system elements to those that require detailed simulations based on substantial historical time-series data. One of the most commonly used metric in the latter category is the insufficient ramping resource expectation (IRRE) [4]. It refers to the expected number of times over specific time horizons that a power system fails to cope with changes in the net load. For each time horizon, time-series data of the ramping requirements for the net load is computed from past time-series data of output from all generating units along with synchronized demand data. The upward and downward ramping capabilities available from the fleet of generators are also calculated from their operational characteristics for each time period. Ramp availability data is subsequently matched up to corresponding ramp requirement data to determine the flexibility deficits encountered on the system over the various time horizons. The Electric Power Research Institute proposed a more comprehensive flexibility assessment tool, InFLEXion, which integrates four flexibility adequacy metrics [15]. In addition to IRRE, InFLEXion uses period of flexibility deficit (PFD) and expected unserved ramping (EUR) to measure the number of periods when the power system is likely to experience flexibility shortfalls in a given direction during a particular time horizon and the total magnitude of these deficits respectively. The fourth metric, flexibility well-being, extracts information from EUR and PFD to categorize the power system in a user-defined safe, warning, or dangerous state [15]. Other tools, such as REFLEX [11] and FAST version 2 [16], involve an assessment of potential flexibility capabilities of the generation resource fleet as part of the detailed simulation of power system operation.

Simpler and less data-intensive flexibility metrics consider primarily the physical characteristics of the power system resources without delving into operational details. Yasuda [17] proposed a flexibility chart that provides a glimpse of the potential flexibility resources in a power system. The percentages of installed capacity, pumped hydro, hydro, combined cycle gas turbine, combined heat and power, and interconnection relative to peak demand are graphically illustrated. However, information conveyed by the chart is limited as capacity alone is not a suitable indicator of flexibility. Kirby and Milligan [18] observed the operating range together with the up and down ramping rates of each generator to determine the aggregate ramping capability available in a power system on an hourly basis. It was then compared with hourly load data to assess whether the available system flexibility is able to meet the required flexibility needs. Brouwer et al. [19] identified minimum generation level, ramp rate, start-up time and its associated cost as key flexibility parameters of a thermal power plant. These parameters were subsequently applied as constraints in power system models in order to assess the technical and economic operation of power plants in distinctly diverse future power system scenarios. FAST version 1 [20] quantifies the available flexibility from generating units for four different time horizons ranging from 15 min to 12 h, in terms of up and down ramping rates. Assumptions are made to cater for flexibility provision through storage, interconnection and demand response. The maximum load variability on the power system which can be met by its combined flexibility resources is then estimated. Ma et al. [21] devised a promising offline flexibility index that estimates the contribution of individual generators to the overall system flexibility based on their technical parameters. In order to determine the flexibility of each generator, the authors considered two important technical characteristics. Firstly, the capability to respond quickly to changes in load, given by the average of ramp-up and ramp-down rates, and secondly, the adjustable capacity, calculated as the difference between the maximum and minimum stable generation capacity levels. The index is then normalized with respect to the maximum capacity of the generator. The appeal of this index lies in its simplicity and its intuitive ability to compare the flexibility of individual generators in a power system.

Both categories of flexibility metrics identified in the foregoing literature review have their limitations when they are applied to power system planning. The use of approaches that are heavily reliant on past chronological data is restricted by several factors. Firstly, they require a considerable amount of data together with detailed simulations of balancing load and generation at small temporal resolutions over long time horizons. Unfortunately, not all power systems have historical databases of load synchronized with output power from all conventional and intermittent renewable energy generators. Another caveat of these tools relates to their exploitation of historical data to evaluate the degree of uncertainty and variability that can be envisaged in future power systems. In particular, the past generation output from RES determines the anticipated variability in net load. But renewable regimes are intrinsically dynamic and depend on the complex interplay of many climate factors. Their inconsistency has been exacerbated by climate change [22–24]. Studies have pointed to the unreliability of counting on present and past RES studies to adequately characterize future output [25–27]. Given the wide uncertainty range, estimates of ramps in variable renewable energy production from past output changes can be misleading, predominantly in long-term energy planning studies. Finally, traditional long-term power system planning is a highly constrained, large-scale, mixed-integer nonlinear programming problem [28,29]. Integrating computationally intensive flexibility calculations in an already convoluted problem will significantly increase its complexity.

These limitations do not apply to the category of simpler metrics, making them ideal for the flexibility assessment of potential generation mixes in long-term power planning. Nevertheless, some inadequacies have been identified in the formulation of the metrics. Most of them consider only ramp rates and operating range when determining the flexibility supplied by generators. Yet, there are several other technical characteristics of a generator that influence its flexibility level. Features such as start-up, shutdown, minimum up and down times have not been taken into account in the existing metrics. Moreover, the current operational state of a generator is key in establishing the extent of flexibility it can supply [16]. For example, if a generator has recently been shut down, it will be able to come online only after the minimum down and start-up times have elapsed, highlighting the significance of these factors. Another important issue relates to the relative importance assigned to the technical characteristics of a generator when computing its overall flexibility. For example, Ma et al. [21] assumed that average ramp rate and operating range have equal importance in determining the flexibility of a generator. Accordingly, equal weightage was assigned to the two characteristics